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An Investigation Of Service Degradation In Long-term Human-robot Interaction With a Particular Reference To Recharge Behaviour

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Abstract

Autonomous long-term operation of social robots has always been a challenge in Human robot-interaction. Social mobile robots acting as companions or assistants will need to operate over a long-term period of time (days, weeks or even months) to perform daily tasks and interact with users. Therefore they should be capable of operating with a great degree of autonomy and will require sustainable social intelligence. Social robots are fallible and have their own limitations with the service they provide. One of the most important limitations of mobile robots is power constraints and the need for frequent recharging. Social mobile robots generally draw power from batteries carried on the robot in order to operate various sensors, actuators and perform tasks. However, batteries have a limited power life and take a long time to recharge via a power source. While the recharge behaviour is active, which may impede human-robot interaction and lead to service degradation. This thesis raises some important issues related to recharge behaviour of social mobile robots which appear to have been overlooked in social robotics research.

This work investigated service degradation in long-term interaction due to recharge behaviour of autonomous social mobile robots and proposes an approach to manage service degradation due to recharge. First we performed a long-term study to investigate the service degradation caused by the recharging behaviour of a social robot. Second we conducted a more focused social study which helped to understand user's attitudes towards a mobile robot with respect to recharge activity. We explored a social strategy by modifying the robot's verbal behaviour to manage service degradation during recharge. The results obtained from our social study indicates the use of verbal strategies (transparency, apology, politeness) made the robot more acceptable to the users during recharge. We believe that social mobile robots should behave in a socially intelligent manner while managing service degradation. We also provide some recommendations for social mobile robots to manage their recharge behaviour in this thesis.

Keywords: Long-term interaction, service degradation, companion robots, recharge behaviour, social intelligence, user expectations.

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Chapter 1

Introduction

It has been predicted that in the coming years, social robots will be part of our daily lives in domestic and work environments. According to the report by World Robotics, in 2013 alone about 4 million service robots for personal and domestic use were sold, 28% more than in 2012. Projections for the period 2014-2017 state, about 31 million units of service robots for personal use to be sold [6]. As social robots find a role in our everyday life, it is important to study the social interactions of humans with robots over a long-term period. The study of long-term interaction with social robots in real social settings can provide us with valuable insights into various social and practical issues in developing and designing socially acceptable robots [7].

Robots are fallible and have their own limitations in many ways and will continue to be so for the medium or even long-term [8, 9]. The classic strategy for dealing with this, seen in industrial robots, is to engineer the environment to make it easier for the robot [10, 11]. However, in human social environments it may be very challenging and sometimes infeasible to engineer the social environment. So can we engineer the social context to change user expectations by giving the robot social strategies? We know that expectations are flexible - the uncanny valley [12] shows that the degree of "human-likeness" impacts the perceptions of human interaction partners.

Also setting the right expectations about a robot's capabilities and service degradation can influence users' perception and acceptance of the robot [13, 14]. Expectancy-setting and recovery strategies can be effective in mitigating the negative impact of a robot's service error on users' impressions of a robotic service [15]. In this thesis we investigated this in the context of one of the most important limitations of mobile robots - power constraints and the need for frequent recharging.

1.1 Motivation

Social mobile robots will need to operate over a over a long period of time, i.e. days, weeks or even months in order to perform daily tasks; hence they should be capable of operating with a great degree of autonomy and will require sustainable social intelligence [16]. In order to operate various sensors, actuators and perform tasks, autonomous mobile robots generally draw power from batteries carried on the robot [17]. However, batteries have a limited power life and take a long time to recharge via a power source. The batteries must be recharged either manually by a human or through an autonomous recharging capability [18]. While the recharge behaviour is active, the robot may be prevented from performing its normal tasks and this may hinder the flow of human-robot interaction (HRI) and lead to service degradation.

Earlier studies [19], [20] indicate that battery life and long recharge times break engagement between robots and their users and can pose a challenge to long-term social bonding as well as acceptance of social companion robots. Due to health and safety reasons a robot charger or docking station cannot be placed in the middle of a room [21]. Hence the robot has to stay near a wall while recharging, thus becoming immobile and less accessible to the user. This can become a barrier in HRI and even unacceptable for the user.

It is therefore important for social mobile robots to demonstrate social abilities to manage service degradation due to recharging. Moreover, they should also be able to mitigate the user's disappointment at not being at service while recharging, in a socially intelligent manner. According to Dautenhahn [16], *Socially intelligent Robots show aspects of human-style social intelligence, based on possibly deep models of human cognition and social competence* [22]. Thus, in HRI the term social intelligence is used in the context of human-style social interaction and behaviour by the robot. In the context of this thesis, the robot needs to produce behaviours towards the human that are comfortable and socially acceptable to manage user's expectations while undergoing a service degradation due to recharging.

We anticipate that service degradation due to the recharge behaviour of the robot may be negatively perceived during long-term interactions. Typically, long-term human-robot interaction studies are conducted in a controlled environment with repeated interactions on a fixed task rather than continuous operation [23]. Thus, the aspect of managing service degradation while recharging appears to have been overlooked in social robotics. We aim to investigate this novel area, exploring the use of social strategies during recharge behaviour for mobile robots to manage service degradation in a socially intelligent manner.

1.2 Aim

To study the impact service degradation of the robot due to its recharge activity during long-term human-robot interaction and to propose an approach during recharge to manage user expectations in a socially intelligent manner.

1.3 Objectives

- Develop robust navigation, auto-recharging and ubiquitous user presence detection capabilities for a robot that can operate over a long-term period with users.
- Establish the main power consuming factors for a mobile robot by conducting long-term navigation runs.
- Investigate the social impact of service degradation due to robot's recharge activity on human-robot interaction by means of a long-term experiment.
- Propose an approach during recharge that can manage user expectations in a socially acceptable manner.
- Provide design recommendations for power management and recharge behaviour during long-term human-robot interaction.

1.4 Research Goals

In this work, we investigate the impact of service degradation due to the recharge behaviour of a robot during its long-term interactions with users and on how the users perceive it. We hypothesise that mobile robots having a socially intelligent recharge strategy will be more acceptable to the users. We expect to find answers to the following research questions:

- How does the robot's recharge behaviour impact the user's perception of the robot?
- How does service degradation of the robot during recharging impact its social perception during long-term interaction?
- What strategies employed by the robot can provide a socially acceptable solution while it is recharging?
- Can the use of verbal strategies have a positive impact on acceptance of the robot while it is recharging?

1.5 Thesis Structure

This thesis is structured into 7 chapters. In Chapter 2 we introduce background work on social handling of mistakes and limitation of robots, power autonomy and long-term interaction. Chapter 3 describes our approach based on some ideas adopted from background work. We started by designing and building a robotic platform and a robust recharging mechanism which could be used for performing long-term experiments. Chapter 4 describes two preliminary pilot experiments, first to understand the power usage characteristics by the robot and second to understand user's perception during long-term interaction. Both these experiments provided insights into the technical and social challenges which helped to refine our approach. In Chapter 5 we performed a long-term study with 5 participants for 3 weeks which highlighted the social challenges caused due to robot's recharge activity. We made some design recommendations for managing the recharge behaviour of the robot following the long-term study. We then carried out a social study with 50 participants reported in Chapter 6 focusing on the use of verbal strategies by the robot and investigated the users' perception of the robot during recharge. Finally, Chapter 7, provides some concluding remarks, outlines the contributions of this thesis, and the future directions this research might take.

Chapter 2

Background

In this chapter we describe existing research work relevant to this thesis. We have structured this chapter into 3 main topics. Long-term HRI poses greater technical and social challenges, earlier work has shown that the use of social strategies by the robot can help to overcome some of the technical challenges and limitations of robots in HRI. Hence, we start by describing various approaches on social handling (verbal/non-verbal) strategies that can be used by the robot to manage the mistakes, limitations of robots and user's expectations in Section 2.1. We then describe the main challenges for power autonomy in Section 2.2, important for long-term survival of an autonomous mobile robot system. Since the work described in this thesis is relevant to long-term human-robot interaction (HRI), we discuss relevant work relating to long-term studies carried out in different social environments in Section 2.3. We then finally summarise some key findings from this chapter in Section 2.4.

2.1 Social Handling: Mistakes, Limitations and Expectations

The fact that short battery life and long recharge time may influence human-robot interaction means it is imperative that researchers consider the social elements of human-robot interaction that allow individuals to properly calibrate their reliance on these systems. The current state-of-the-art robotic technology is limited in its ability to handle uncertain situations and it is inevitable that service robots will make mistakes. For instance, a hospital delivery robot may interrupt nurses dealing with an emergency [8]. Mistakes while providing service can affect people's acceptance of the robot and lead to disappointing users. People are often found to be upset when there is a service breakdown, and can be more dissatisfied by a failure of the recovery than the mistake itself [9].

Mobile robots will have their own limitations with battery life and will make mistakes while performing tasks over a long-term period. Earlier studies indicate that humans do hold robots accountable for their mistakes, at least more so than they would an inanimate object such as a vending machine, as reported in the study by Kahn et al. [24]. It is therefore important to look at literature on social handling by robots to manage user expectations and limitations of robots. It is suggested that if the robot is more transparent about its ability, intent and internal state then it might help to manage users' perceptions of the robot in a positive manner (Hanheide et al. [25]).

Research suggests that transparency has positive effects on people and improves acceptance of the system. In HCI, Herlocker et al. presented experimental evidence showing that explanations can improve the acceptance of automated collaborative filtering (ACF) systems [26]. They first categorised the sources of error for ACF systems as model/process errors and data errors. Providing explanations for these errors, gave users a mechanism for handling errors associated with a recommendation. While the idea of transparency has an intuitive appeal, few studies have examined the impact of transparency on human-robot interaction.

In a previous study by Kim and Hinds [27], transparency was operationalised as the user's understanding of why a machine (in this case a robot) behaved in an unexpected way. They defined transparency as the robot offering explanations of its actions. In their experiment transparency also had two levels: low transparency and high transparency. In both cases the robot showed an unexpected behaviour - it suddenly spun three times in one place. For the high transparency conditions, after the unexpected behaviour the robot explained the reason for its action by announcing "I have recalibrated my sensors." For the low transparency conditions the robot offered no explanation. They found that when the robot explains its behaviour (e.g. is transparent), people blamed other participants in the study (but not the robot) less.

Lyons [28] proposed a model of human-robot interaction including key elements of robot-to-human transparency. This robot-to-human transparency model includes factors like: an intentional model, task model, analytical model, and environmental model. Lyons also suggested that the robot-to-human communicative interface should naturally involve a voice or text exchange between the human and the robot. However, the physical interface could also include features such as robotic emotional expression and gestures, which in combination are effective in communicating a robot's emotional state [29]. To further elaborate the point about transparency we describe some studies which used both the verbal and non-verbal abilities of the robot.

2.1.1 Transparency: Non-verbal Interaction

A long-term human-robot cohabitation experiment by Lehmann et al. [30], involved two professional artists living in a Robot house (adapted for Human-Robot Interaction studies) for a period of one week. The artists lived in the Robot House full-time along side various robots with different characteristics in a smart home environment. The artists immersed themselves in the robot populated living environment in order to explore and develop novel ways to interact with robots. The main research aim was to explore in a qualitative way the impact of a continuous week-long exposure to robot companions and sensor environments on humans. These experiments involved gaze tracking during social interaction, the expression of non-verbal cues as indicator for intended actions, the use of a robot in remote communication and a sensor grid to log daily routines and analyse behavioural patterns. At different stages of the scenario the participants were asked specific questions concerning how the robot should perform the particular task and why (i.e. “Should the robot make any sound and if so, what kind of sound?”; “Should the robot display something on its colour LED display?”; “Where should the robot position itself?” etc.). Both the users supported the idea of the robot using its LED colour display as a status indicator for battery charging level (refer Figure 2.1).

Figure 2.1: Experiment at the Robot house with a Care-O-Bot 3.

Further analysis on the above study by Koay et al. [31] investigated robot etiquette, in particular focusing on understanding the types and forms of robot behaviours that people might expect from a robot that lives and shares space with them in their home. The experiment was intended to tease out the reasoning behind participants’ choices and preferences. The participants gave suggestions for passive robot behaviours that could complement the robot’s active behaviours in order to allow the robot to exhibit considerate and socially intelligent interactions with people. The experiment involved the experimenter collecting information from the artists with regard to how they preferred their Care-O-bot robot to behave and interact with them within the scenario.

This study involved the robot using two of its main expressive channels, sound (beep or tune) and the LED colour display to provide cues to signal a) the potential level of hazard of the current robot task/action, and b) the state of the current robot task. Feedback related to the default location of the robot while it is at charging point, showed that participants preferred: an Amber colour when charging (i.e. fading in and out, with adaptable intensity depending on environment's lighting condition), and a green colour when it is fully charged. In feedback on when the robot leaves the charging station and approaches the user, participants preferred: the robot making a noise to indicate it is about to move, blinking green when it is moving and a green colour when it stopped. These behaviours may form important aspects of robot etiquette. The experimental results presented above have limitations (i.e. only two participants were involved, both have experience with robots and are not in the age group of the target users), and may not be generalised for all robots and users.

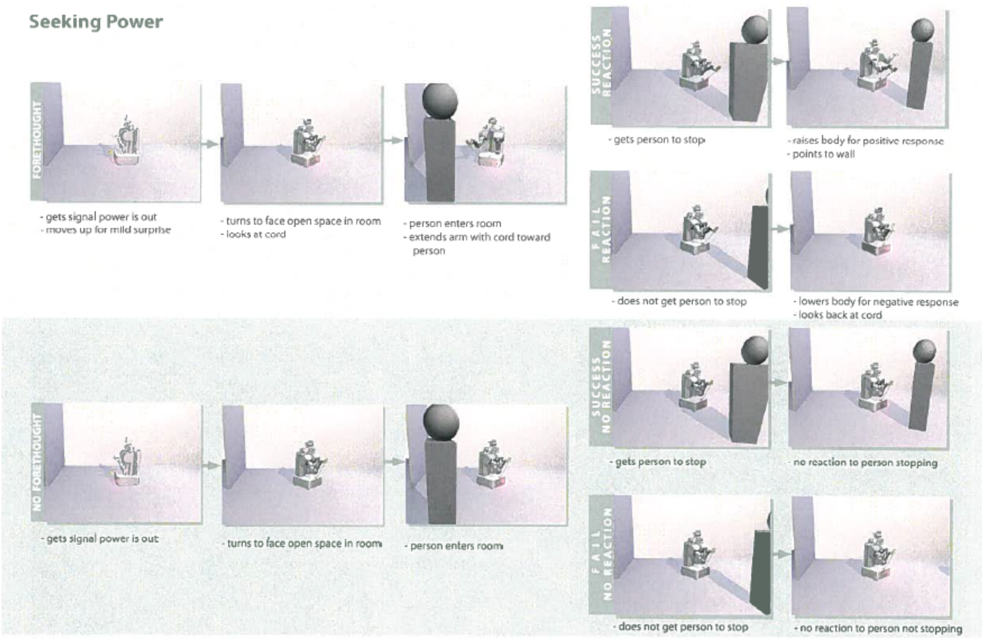


Figure 2.2: Frames from two of the animations: Recharge scenario- there were two possible pre-action animations (showing forethought or no forethought), two possible functional task outcomes (success or failure), and two possible post-action animations (showing a reaction to the task outcome or not) [32].

A study with the PR2 robot by Takayama et al. [32] drew ideas from principles of animation, they were able to illustrate forethought and reaction. By employing techniques of engagement, confidence and timing, they were able to help people read robot behaviours with more certainty. For the purpose of this study, four tasks were selected in order to cover a variety of activities: opening a door, delivering a drink to a customer, ushering a person into a room, and requesting help from a person to plug into a power outlet for recharging, refer figure 2.2. They performed an online video prototype experiment (N=273), and found that perceptions of robots are positively influenced by robots showing forethought, the task outcome (success or failure), and showing goal-oriented reactions to those task outcomes. They found that showing forethought makes people more sure of their interpretations of robot behaviour, and makes the robot seem more appealing and approachable. The authors also discovered showing a reaction to the task outcome can make the robot seem to be more intelligent/capable, even if it fails to achieve the functional task at hand.

The approaches covered in this section [32, 31, 30] often assume that humans are supervising the robot and are always aware of what the robot is doing. However in a social environment like homes, office/workplace it may not always be the case that users are looking at the robot all the time.

2.1.2 Transparency: Verbal Interaction

With regards to verbal transparency we focus on some studies on apologies and on polite behaviour of the robot used to demonstrate its intentions. Existing research on verbal transparency suggests that use of apology and polite verbal behaviours can positively influence the perception of the robot, hence we cover some approaches in this section.

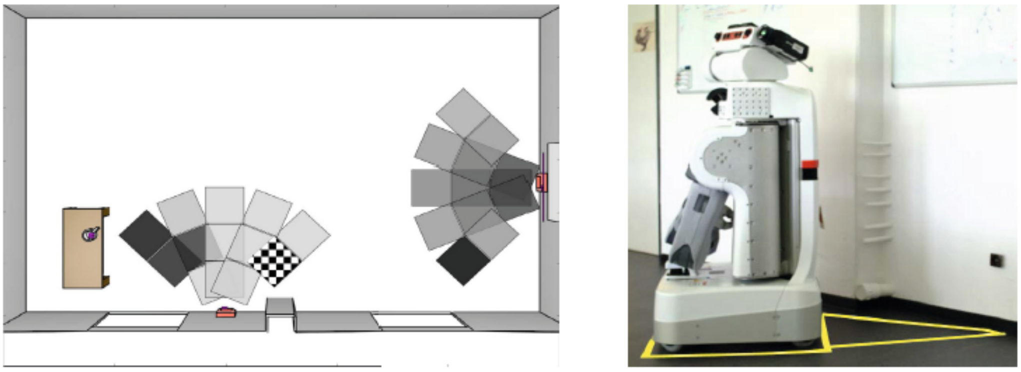
Apology: In a study by Lee et al. [15] with an interactive robot 'Snackbot', (refer figure 2.3) that delivers a personal service incorrectly, a mobile robot delivers the wrong drink. The authors tested different mitigation strategies in an online scenario study with 317 participants. All participants saw a video of one of two service robots, and then viewed a scenario in which the robot either gave correct service or made an error. They investigated people's reactions to the robot's error and to different mitigation strategies (forewarning, apology, compensation, options, and no recovery strategy). The results from the study indicated that breakdowns in robotic service had a severe impact on evaluations of the service and the robot, but forewarning and recovery strategies reduced the negative impact of the breakdown. They also found that an apology strategy was effective in making the robot seem more competent, making the participants feel closer to and liking the robot more.

A study by Jost [33], used a robot to detect the facial expression of the person in order to analyse his/her emotion and express back an appropriate emotion. The experimenter asked participants to imagine the following context: the robot had advised them to watch a movie. When they came back home, two scenarios were investigated. Scenario A: participants did not like the movie and reproached the robot for its advice. Scenario B: participants liked the movie and thanked the robot. In both cases, participants had to observe three possible behaviours and to indicate if the robot

Figure 2.3: Snackbot delivering snacks

provided a credible and sincere answer. In the A scenario, the robot said: “I’m really sorry. This movie has good critics. I thought you liked it.” In the B scenario, robot said:“Thus, you liked the movie! I’m happy to give you good advice.”. The results from this study confirm that during scenario A – when the robot apologised for the wrong advice – the robot was judged credible and sincere. Furthermore, a similar study with a virtual agent, ‘Greta’ [34], provided similar results. When Greta apologised under Scenario A condition, 65% of participants found Greta “rather” sincere (39%) or “totally” sincere (26%) and 70% of participants found Greta “rather” believable (52%) or “totally” believable (18%).

Work by Lindner and Eschenbach [35] proposed the idea of modelling social affordance spaces in relation to the physical placement of a robot while it is recharging. They proposed a model to determine the most socially adequate placement of a robot for an activity, so that the social robot can reason about where its own and others’ activities can be placed (functional level) and how activities of different agents can spatially interfere (social level). They suggested that a robot that is aware of socio-spatial constraints should also be aware of violating such a constraint. The authors suggested that in situations where a robot is likely to violate social constraints, the robot should apologise for the violation or even justify its choice. They further gave an example of a robot choosing a power outlet for recharging and thereby partially blocking a whiteboard. They argued it should explain this behaviour to the user by telling them that recharging is really urgent and the other available choices would lead to blocking a doorway. A robot in need of a power outlet should choose one of the affordance spaces near the outlet close to the whiteboard. The result is depicted in figure 2.4, the robot obtains an affordance space it has most socio-spatial reasons to use.



(a) (b)

Figure 2.4: a) Result of the social activity-placement procedure. Potential agent regions are shaded relative to their social adequacy (the brighter the more adequate). The potential agent region of the selected affordance space is marked by a checkerboard pattern. (b) Robot placement in the lab after navigating to the selected affordance space [35].

Politeness: Work carried in the domain of pedagogical agents by Wang et al. [36] reported on the effect of politeness strategies on students' learning performance. They focused on the manner in which a pedagogical agent communicates with learners, i.e., on the extent to which it exhibits social intelligence. A model of socially intelligent tutorial dialogue was developed based on politeness theory, and implemented in an agent interface within an online learning system. A series of Wizard-of-Oz studies were conducted in which subjects either received polite tutorial feedback that promotes learner face and mitigates face threat, or received direct feedback that disregards learner face. Across all students, a polite agent, compared to a direct agent, had a positive impact on students' learning outcomes. In particular, for students with need for indirect help or who had lower ability for the task, the polite agent was much more effective than the direct agent.

In the HRI domain, the results from the study performed by Nomura and Saeki [37] did not show a beneficial effect of the robot's polite behaviour (non-verbal) on human task performance, but suggested that only human perception of the robot was affected. Another study by Hendriks et al. [38] discovered that people prefer a calm, polite, and cooperative robot vacuum cleaner that works efficiently, systematically and likes routines. A study by Salem et al. [39] investigated how the use of politeness strategies may affect social perceptions of a robot and HRI. For the study, they conducted an experiment in which they employed a receptionist robot intended for use as an interaction partner. The results indicate that the manipulation of the politeness level, although perceived by the participants, had no major impact on participants' perception of the robot and overall HRI experience following the interactions, nor on their task performance.

2.1.3 Managing User Expectations

Expectation can be defined as *"a strong belief that something will happen or be the case"* (Oxford Dictionary). A study by Paepcke & Takayama [13] with AIBO and Pleo robots, indicated that setting expectations about a robot's capabilities influenced users' beliefs about what the robot could do. The results from their study suggested, upon interacting with the robot, people whose expectations were set high became more disappointed with the robot's capabilities than people whose expectations were set low. Furthermore, people whose expectations were set high (as opposed to low) ultimately perceived the robot as being less competent. Another study by Lohse [40] showed that users' expectations are influenced by the robot's behaviour. The author concluded that robot behaviour should be designed to shape users' expectations and behaviour to enable them to more efficiently solve tasks in the interaction. Moreover, it can be assumed that these expectations change based on the situation and on how it is conceptualised by the user. Komatsu et al. described in their study [14], the difference between the users' expectations and the function that the users' actually perceived of an agent as *"adaptation gap"*. The authors suggested that when the users' expectations exceed their perceptions, they would be disappointed by the agent and do not believe the agents' outputs. In contrast, when their perceptions exceed their expectations, they would get interested in the agent and do believe the agents' outputs. The results from their study showed that the participants with positive adaptation gap signs had a significantly higher acceptance rate than those with negative ones. Thus indicating that managing user expectations in HRI can ease social acceptance of robots.

Managing user expectations of robots can be challenging especially when the users have interacted with it before and are aware about its capabilities/limitations. So it is possible that when humans experience a negative unexpected behaviour from a social robot, they will be disappointed and may not accept the social robot as an interaction partner. Conversely it is possible that when users experience a positive unexpected behaviour they can be surprised and may accept the social robot as an interaction partner. We believe by using transparency (explaining more about its limitations) combined with social verbal behaviour from the robot (being more polite and apologetic) about its limitation of recharging can help to manage user expectations. We aimed to formulate our approach in this thesis based on these factors (transparency, social verbal behaviour).

Discussion: Studies by Mutlu et al. [8] and Kahn et al. [24], suggests that users are critical of the mistakes and disruptions during service made by robots. In order to better manage mistakes/limitations, transparency from the robot about its ability, intent and internal state has been shown to have positive effects on people and improved their acceptance of the robot. Studies have also shown that user expectations can be influenced by the robot's behaviour [13, 40]. Recharging can be considered as one of the fundamental limitations of mobile robots, adding more transparency from the robot about its battery limitation and constant need to recharge appears to be an interesting approach to manage user expectations that we investigated in this thesis.

In a study by Kim and Hinds [27], the robot was better accepted when it offered an explanation about its condition than when it made a mistake. Transparency can be expressed through both verbal and non-verbal behaviour by the robot. Koay et al. [31] reported a study with two participants who expressed their preferences about how the robot should indicate it intentions using light or sounds. However, the modality (verbal/non-verbal) of transparency depends on the capabilities of the robot and the social context. For example users might not be looking at the robot all the time (e.g. in workplaces), so expressing intent using verbal/sounds seems a more viable approach. Studies reported by Lee et al. [15] and Jost [33] explored the idea of transparency using verbal behaviours (apology) and found promising results on the robot's acceptance overall. Lindner and Eschenbach [35] proposed the idea of having a socially appropriate placement for a robot while recharging and should apologise in case of violation of social constraints. Although the authors did not study the effects with real users interacting with the robot, social placement and verbal apology from the robot while it is recharging appears to be an avenue for further investigation.

In relation to verbal transparency using politeness, studies conducted on the politeness of virtual agents have shown promising results [36], but most studies on politeness in the HRI domain have not shown encouraging results [37, 41, 39] making this a valid avenue for further investigation. The model proposed for robot-to-human transparency by Lyons [28] using verbal, non-verbal robot abilities can provide a useful guideline for designing future experiments. Also Lehmann et al. [30] reported that the expression of non-verbal cues as an indicator for intended actions of the robot such as the recharge behaviour is important for the users. Although the term 'transparency' can be a bit ambiguous in the examples presented in this section, the core idea behind it appears to be intuitive, but more HRI studies are required to validate this concept.

2.2 Power Autonomy

Power autonomy is an important aspect of a mobile robot system if it is to operate in an environment without human intervention. In this section, we describe some of the key challenges for power autonomy. We begin with battery technology which appears to pose an immediate challenge for long-term operation of mobile robots (Section 2.2.1). In order for mobile robots to be fully autonomous, they should be capable of recharging their batteries without human intervention. Hence, we describe approaches to autonomous charging in Section 2.2.2. Finally, we look at existing work on power autonomy in robotic systems inspired by biological systems to develop approaches to solve the energy self sufficiency problem in Section 2.2.3.

2.2.1 Battery Technology

Autonomous mobile robots generally use batteries as their power source in order to operate various sensors, actuators, computation and perform tasks. However, batteries have a limited power life. The life span of batteries has been a fundamental challenge for long-term interaction with mobile robots. Although computer processing and sensors have become cheaper and more powerful over the years, batteries are still inefficient and slow to recharge. Lithium (Li-ion), Lead acid, NiMH (Nickel Metal Hydride), NiCad (Nickel Cadmium) etc. are the main types of batteries in use for mobile robots. These batteries vary in several important aspects according to the cell chemistry and the technologies used. Choosing a suitable battery technology often involves a trade-off based on characteristics such as cost, charge-discharge properties, weight, charge retention, energy density etc. Some types of rechargeable batteries for example NiCd, NiMH exhibit the so-called memory effect [42], i.e. if they are not fully discharged during several cycles, then the amount of power they can deliver diminishes with time. It is as if the battery would "remember" that, for example, only 50% of its capacity has been used for many consecutive cycles and then, when more power is required, it would not deliver more than 50% of the maximum capacity. The memory effect is also important if the robot decides to recharge and returns to full operation without fully recharging, as this can severely affect its long-term battery health.

The charge/discharge characteristics of the battery are of particular importance as the battery life can become severely affected, if the battery is overcharged or deeply discharged [43]. In the long-term human-robot interaction context, as a battery ages, its capacity is reduced, so it may affect the performance of the robot throughout the battery's lifespan. The depth of discharge (DOD) describes to what extent the battery has been discharged before being connected to a charger and undergoing a full recharge. A commonly used type of batteries in mobile robots is Lead Acid. It may be a bad practice to repeatedly deep cycle Lead Acid batteries as this severely reduces the number of cycles of use that the battery will survive. For example a Lead Acid battery used in a Pioneer robot platform [44], if persistently discharged to 100% throughout its life, it can only expect to provide 180 cycles before its capacity falls to 60% of the specified capacity [45]. The number of cycles increases greatly as the DOD is reduced during its operation. If always drained to 30% depth of discharge for example, the battery would be expected to last 1200 cycles before its capacity dropped to the same

60%. Hence, to preserve the long-term health of a battery it is important for a mobile robot to decide when to engage/disengage in recharge behaviour and this can vary according to the type of battery used on the robot. A comprehensive description of various battery characteristics, advantages/disadvantages and recommended battery types for robots is covered by Cai et al. [1] (refer Figure. 2.5.

Table 1 different types of traction rechargeable battery

Battery type	Operating Voltage /V	Specific Energy /(Wh.kg^{-1})	Energy Density /(Wh.L^{-1})	Cycle Life /times	Self-discharge Rate /%.per month
Polymer Li-ion	3.7	120-170	300-460	≥1000	≤3
Li-ion	3.6	100-160	270-360	1000	6-9
Ni-Zn	1.65	60-75	240	500	-
Ni-MH	1.2	65	200	500	30-35
Lead-acid	2	25-45	80-100	250-450	-
Ni-Cd	1.2	30-50	150	500	25-30
Fuel Cell	-	700 /(W.kg^{-1})	-	≥1000	-
Ultra Capacitor	-	2000-15000/(W.kg^{-1})	-	≥1000	-

Table 2 Advantages and disadvantages of each battery type

Battery type	Advantages and short comments	Disadvantages and short comments
Polymer Li-ion	Promising technology, very high specific energy and energy density, long life, shape can change arbitrarily, safe.	High cost, limited capacity and discharging rate, only "credit card" form currently available.
Li-ion	High specific energy and energy density, long life	High cost, complexity of operation circuit, heating at high discharging rate.
Ni-Zn	New emerging technology, relative high specific energy and energy density.	During research & development, few commercial applications.
Ni-MH	Developed technology, relative high specific energy and energy density, more and more widely used, acceptable cost.	Limited charging rate.
Lead-acid	Developed technology and most widely used, low cost	Low specific energy and energy density, environmental concerns.
Ni-Cd	Very stable discharging voltage, high discharging rate.	Serious environmental concerns.
Fuel Cell	Emerging technology, high specific energy, long life.	Very few commercial applications.
Ultra Capacitor	Emerging technology, high specific energy, long life.	Very few commercial applications.

Table 3 recommended battery type for some typical applications

Application requirements of battery system	Examples of mobile robot	Recommended types
Low requirements on mass and size	Wheeled	Lead-acid, Ni-MH
High requirements on mass and size, the less the better; high power demand	Humanoid robot	Li-ion, Ni-MH, Ni-Zn, Polymer Li-ion
High requirements on mass and size, the less the better, middling power demand	Wall climbing robot	Ni-MH, Li-ion, Ni-Zn

Figure 2.5: Battery types, advantages/disadvantages and robots, [1]

A common challenge in all battery technology is the low continuous operational and comparatively high recharge time. A widely used research mobile robot platform, the Pioneer P3AT robot manufactured by Adept Mobilerobots [44] uses Lead acid batteries and has an on-board computer that takes about 3 hours to recharge and delivers about 3 hours of operational time depending on usage. A popular commercial vacuum robot, Roomba[46] uses NiMH batteries and takes about 2 hours to recharge and delivers about 1 hour of operational time on a single recharge. A Honda humanoid robot can barely walk for 30 minutes with a battery pack on the back [17]. Table 2.1 provides a summary of some popular robots used in research, their operational, recharge time and the recharge mechanisms they use.

Fig.	Robot	Platform Type	Battery Type	Operational Time (hours)	Recharge Time (hours)	Recharge Mechanism
1	ASIMO [47]	Humanoid	Lithium-ion	1	Manual	N/A
2	Nexi [48]	Self-balancing	Lithium-ion	0.75	N/A	N/A
3	FLASH [49]	Self-balancing	Lithium-polymer	2	2	Manual
4	NAO [50]	Humanoid- H25	Lithium-ion	1.50	2	Manual
5	PR2 [51]	Wheel-Mobile	Lithium-ion	2	N/A	Autonomous (electric outlets)
6	PeopleBot [52]	Wheel-Mobile	Lead Acid	3	3	Autonomous (extra attachment)
7	Roomba [53]	Wheel-Mobile	Nickel-metal hydride	2	1	Autonomous (selected models)
8	Care-o-bot [54]	Wheel-Mobile	Lithium-ion	4	4	Autonomous
9	Paro [55]	Static	N/A	1.5	N/A	Manual
10	Pleo [56]	Static	Lithium Polymer	1	3	Manual
11	SCITOS A5 [57]	Wheel-Mobile	Lead-acid	10	5	Autonomous (Visual localisation)
12	Sunflower [58]	Wheel-Mobile	Lead-acid	4	4	Manual
13	Aibo [59]	Legged-Mobile	Lithium-ion	1.5	2.5	Autonomous (Visual localisation)

Robot Figures

1 2 3 4 5 6 7 8 9 10 11 12 13

Table 2.1: Robots Battery and Recharge Summary. Some data collected and reported in this table is an approximation. Some research groups/companies had to be contacted in order to gather this information where there was no information stated formally on other resources. N/A means these details could not be obtained.

As we see from the examples summarised in Table 2.1, if a mobile robot has to perform tasks over a long period then it would spend about the same amount of time recharging itself as performing tasks. It is true that battery technology is constantly improving and emerging technologies like fast charging solutions [60], may eventually charge in a matter of minutes, rather than several hours. However, these new technologies seem years away and too expensive to put into use for current state-of-the-art mobile robots. This encourages the idea of having behaviours produced by the robot while it spends time recharging so that it's not completely useless during recharge. We in this thesis have proposed an approach based on verbal behaviour while recharging.

2.2.2 Autonomous Recharging

In terms of power autonomy, battery operated mobile robots should be capable of recharging themselves without human intervention if they are to be truly autonomous. Autonomous recharging is a major challenge for long-term operation of mobile robots. There have been several approaches in developing auto-recharging mechanisms. Commonly they involve 3 main steps: finding the charger; approaching the charging station; and plugging into the charger (in the case of wireless charging, coming close to the charger). Most of the approaches involve navigating to the charger where visual markers are used as beacons. Essentially, there is a trade off between efficiency and accuracy while designing auto-charging mechanism for a robot. The recharging approaches discussed in this section gives an overview of the technical challenges of autonomous recharging. We categorise the approaches presented in this section primarily into Direct Contact Charging and Inductive/Wireless Charging.

Direct Contact Charging: In the late 1940's Grey Walter developed perhaps the first autonomous recharging for mobile robots, "Tortoises" [61]. These robots used a light following behaviour to find their way into a 'hut' containing a light beacon and a battery charger that made electronic contact when the robot entered. Grey's three wheeled robotic vehicle, which came to be known as "Grey Walter's turtle", had two motors, one for progression by the front wheel dragging the hind wheels like a child's tricycle and one for turning the front wheel. The robots consisted of: a shell with a photocell on its top, a bumping sensor, two motors, two radio tubes, and a battery (refer Figure. 2.6). One of the motors was used for translating, the other for steering. The light sensor was connected to the steering motor.

This configuration allowed the robot to explore its environment. When it did not detect any light, the robot turned on its two motors, describing a cycloidal trajectory. The steering motor also rotated the photocell in search of a light stimulus. This combination of actions generated an exploratory behaviour. If the photocell detected light, the steering motor was turned off, causing the robot to move toward the light stimulus. However, if the light stimulus became too strong, the robot turned away from the light. This ensured the robot would not stay under the light the entire time.

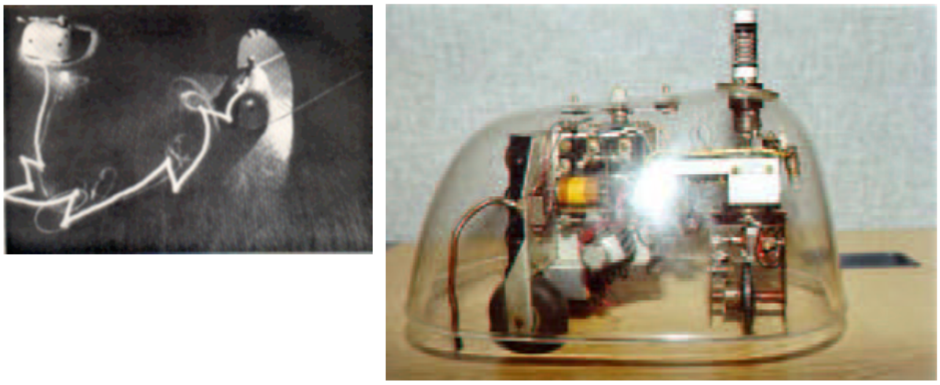
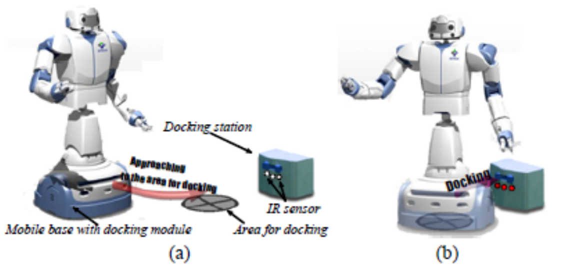


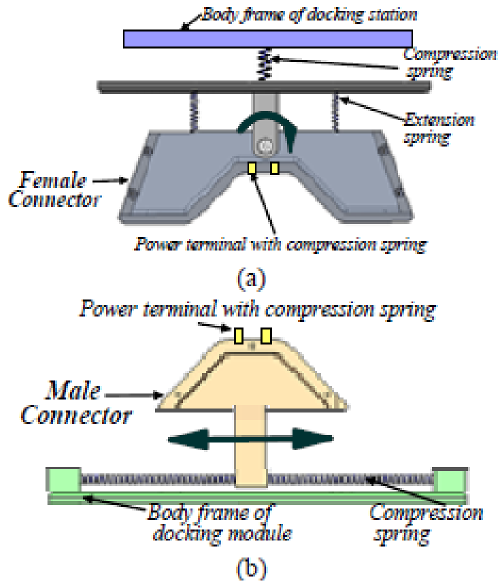
Figure 2.6: Left: Turtle robot about the size of a football is shown by a double exposure and by the trail of light that shows the looping cycloid by which it moved toward the illuminated hutch (charging station) with its front steering-driving wheel. Right: The robot consisted of a shell with a photocell on its top, a bumping sensor, two motors, two radio tubes, and a battery, [61].

This last behaviour depended on the voltage level of the battery. If the battery level was below a threshold, the photocell amplifier increased its gain to detect the light from farther away. Then, when the robot detected light, it ran towards it. However, since its battery was low, the amplified light signal remained below the threshold that would cause the robot to run away. Therefore, in this low power condition, the robot would continue approaching the light source. In order to use this behaviour for feeding the robot, a light bulb and a recharging system were placed inside a hutch. When the robot got into the hutch and the recharging system was activated, the motors were disconnected. Once the battery was recharged, the motors were reconnected and, because both the battery voltage and light intensity were above their thresholds, the robot ran away from the hutch. The design was simple and effective. However, there is no evidence that the recharging of the batteries was automatic or even that it really existed. In order for the robot to recharge its batteries automatically, the recharging system would have had to have some kind of alignment process that was not described in Walter's literature. It is interesting to note that Walter referred to his robots as an "Imitation of Life" [62]. The basic idea for recharging in this work was adapted by some approaches described as follows.

In the late 1990's, Hada and Yuta proposed an approach for long-term automatic charging [63]. Later, they performed a long term experiment [64] with their robot which survived for over a week while repetitively going in and out of the battery charge station every 10 minutes. The aim of this work was to develop an autonomous mobile robot which could perform many kind of tasks in a real environment for a



(a) Scenario for docking. (a) Step 1: Approaching to the area for docking. (b) Step 2: Docking procedure



(b) Configuration of docking mechanism. (a) Female connector of docking station. (b) Male connector of docking module.

Figure 2.7: Docking mechanism, [2]

long duration without any support by humans. Segon et al. [2] presented a docking mechanism with a localisation error-compensation capability. Their proposed mechanism uses a combination of mechanical structure and magnetic forces between the docking connectors. Their docking mechanism had a design to improve the allowance ranges of lateral and directional docking errors, so that the robot is able to dock into the docking station. As shown in Fig. 2.7a, the robot moves to an available area for docking using its range sensors such as sonar (Step 1). When the robot reaches this area, it approaches a docking station using information from the IR LED sensors attached to the docking station, as shown in Fig. 2.7b (Step 2). This docking process is carried out only with the hardware and software attached to the docking station and docking module without any help from other sensors or mechanisms on the robot. Having a compliant docking mechanism can reduce dependency on the robot controlling the final adjustments for docking and allows easy docking with only mechanical configuration. However, the work by Hada [63] and Segon et al. [2] by did not appear to investigate the user's perception of the recharging activity of the robot. Considering the social implications of recharging activity seems to have been overlooked in HRI. In the work carried out in this thesis we investigated the social perception of users on recharging activity of the robot.

Seungjun [65] proposed a docking system similar to an aircraft landing. The robot approaches the recharging station and begins to align itself to the AC power plug when the alignment guidance is visible. When the robot is in proximity to the station, a laser range finder was used to align the robot to a grid with a pattern designed to distinguish it from the surrounding environment. Cassinis et al. [66] designed an electro-mechanical part, consisting of a station into which the robot can dock. It can then wait during the charge and a software part to program the robot with essential operations it has to execute to reach the docking-charging station. They used two lamps on the charging station that act like active markers, these could be better seen by a camera as they emit light, helping the robot to navigate successfully towards the charging station. Their approach was inspired by an ancient navigation aid called Bowditch [67] used by ships. The light pairs indicate a specific line of approach when they are in line. The higher rear light is placed behind the front light which aids the navigation depending on the position from where the light pairs are seen, refer Figure. 2.8. It uses a vision system to find these markers and calculate its displacement so as to home into the charging station. On entering the station the contacts on robot's front side exactly fit into the matching electrical contacts mounted on the charger.

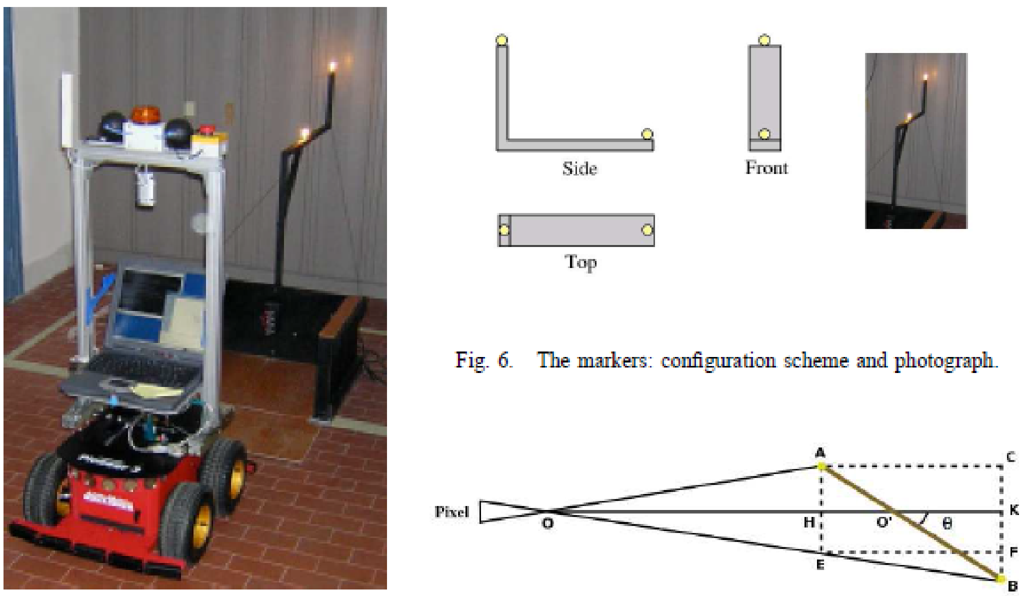


Figure 2.8: Robot entering the charging station on left and markers configuration scheme, [66]

Silvermann et al. [68] developed a docking system which allowed a high angular and displacement error during the docking process. A combination of vision and laser beacons was deployed to perform the autonomous recharging of a Pioneer 2DX robot. The docking station is designed with 2 DOFs, providing compliance for numerous robot docking angles and conditions. Vision was initially used to find the docking station using the robot's pan-tilt-zoom (PTZ) camera. An orange coloured piece of paper was mounted on the wall above the docking station acting as the vision target, and this attracts the robot towards the docking station. The laser range-finder on the robot scans for this beacon and upon detection determines its angle to the wall. This information was used to orient the robot with the docking station. At a distance of approximately 55cm from the docking station, the robot executes a turn as shown in Figure. 2.9. The robot may enter the docking station with a high probability of success within a total entry angle of 12". At this position the robot will initiate a turn and blindly move towards the docking station until the drive motors stall. When electric contact is made, the IR-LED mounted at the top of docking station turns off which triggers the robot to stop. Results of the 100 trials showed a 99% success rate for mechanical docking, and a 97% success rate for electrical docking.

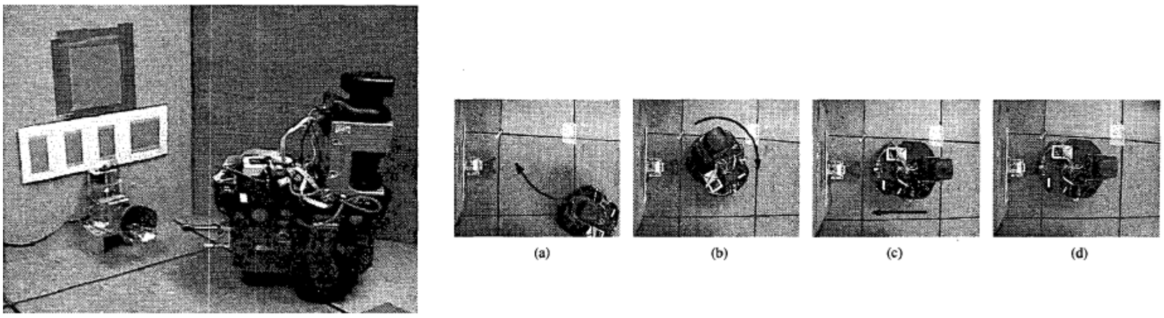


Figure 2.9: Recharge station set-up and docking sequence a, b, c, d (arrows indicate the trajectory of the robot)

A similar approach was adopted by Luo [3], where an artificial landmark is detected and recognised by the proposed image processing system. Then, the geometrical relationship between the robot and the docking station (the depth and orientation) is estimated. The robot moves directly right in front of the docking station. Finally, the robot approaches the docking station. They proposed a virtual spring model, in which the robot and the docking station are connected by a virtual spring. The compliant forces act both in the direction of the translation deformation and bending (refer Figure. 2.10). In work done by Su et al. [69], the docking station was designed with a multiple degrees of freedom connector, providing an optimal docking angle for the mobile robot. The auto-recharging process uses multiple sensors and a laser range finder located on the mobile robot. The mobile robot uses its laser range finder to search for the landmark of the assigned docking station and computes a motion trajectory to move forward to the docking station. The docking station supplies a charging current to the mobile robot by means of a charger.

Michaud et al. [70] developed a robot that contains two charging pins protruding from its back with an infra-red sensor ring used to detect the charging station. Docking was achieved via the robot driving backwards into the charging station. Contact switches must be activated to allow power to flow to the batteries, using a micro-controller for the logic. The charging station was designed to recharge the batteries as fast as possible. The robot docking mechanism was attached to the back of the robot. Mounting this on the back of the Pioneer robot requires the robot to drive backwards blindly into the docking station, since all useful sensors are located in the

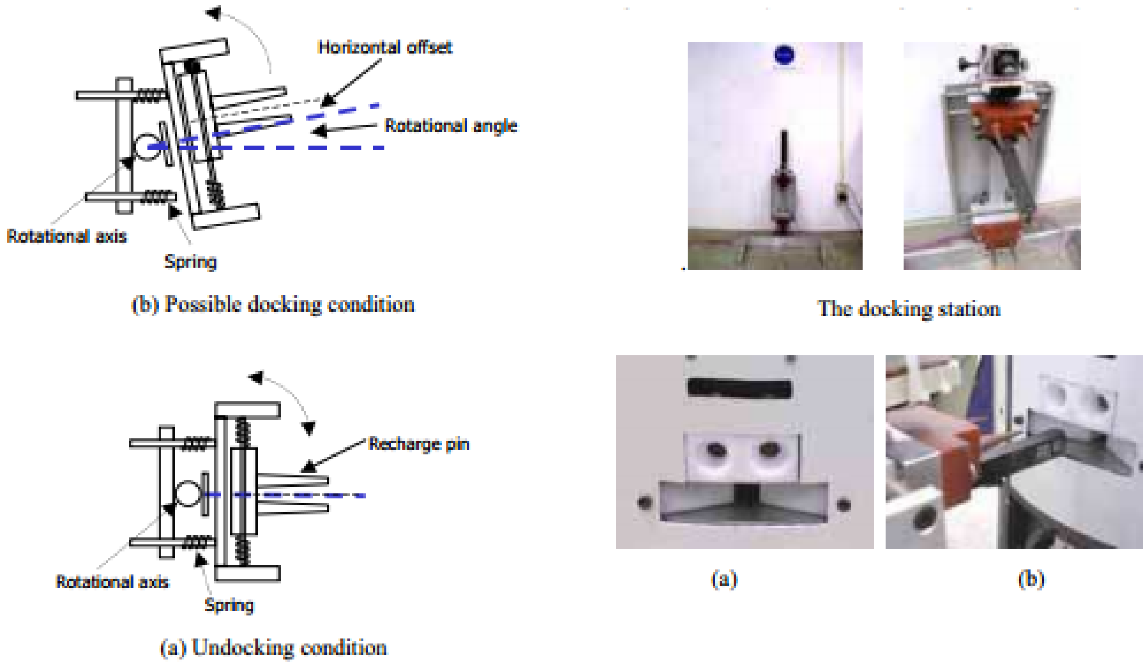


Figure 2.10: Docking Station, (a) Undocking condition, (b) Docking condition, [3]

front (i.e. camera, laser range-finder, etc.). Also, additional motion adjustments are necessary to orient the robot with the docking station (i.e. turning around to align the docking mechanism properly), instead of driving forward if using vision for example. These issues resulted in an interesting docking strategy. If the robot is unsuccessful at docking after the first attempt, it will move away from the docking station a short distance (approximately 1-2cm), and attempt to dock again. After three repeated failures, the robot will drive away and manoeuvre to use vision, repeating the docking procedure. To accommodate unsuccessful attempts, the minimum battery voltage level includes a margin of error for these processes. Having a contingent behaviour to sense a docking failure and re-attempt docking can be useful for mobile robots to manage docking failures. As docking failures can disrupt service provided by social robots and can negatively affect their perception and use by users. Previously discussed docking approaches [2, 65, 66, 68, 3, 69] did not seem to manage the issues of docking failures.

Charging From Power Sockets: In 1964, the Hopkins Beast robots (Figure 2.11) were built at the Johns Hopkins University Applied Physics Laboratory. These robots were able to navigate the corridors using sonar. When they ran out of power, they looked for outlets to recharge themselves. One of the Hopkins Beasts found the power outlets by feeling along the walls. Another used photocells to optically find the outlets from a distance. The outlets had to contrast with the wall in order for this to work.

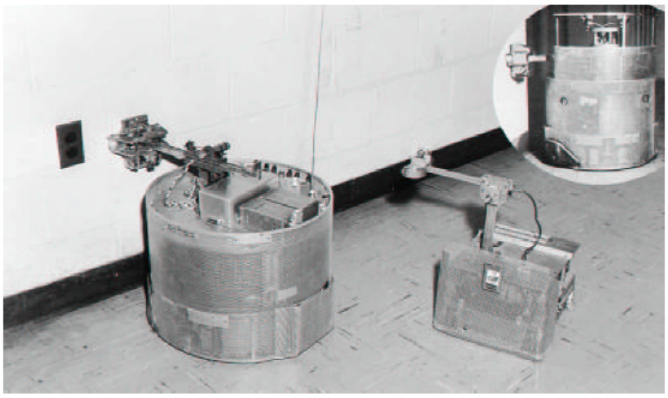


Figure 2.11: Hopkins Beast robots

Work by Torres-Jara [71] acquired electric energy from the power outlets in the walls. The energy from the power outlets was used to recharge the robot's batteries. Therefore, their robot had skills such as: searching for power outlets, connecting to power outlets, and recharging its batteries. Similar work by Mayton[72] and Bustamante [73], explored the idea of using electric outlets as a means to recharge the robot battery using an electromagnetic sensor to localise electric outlet holes, since standard electrical outlets are widely available in most parts of home and office buildings. This approach allows a robot to travel less distance in comparison to a custom built charging station located in one section of the building. The robot can then look for an unobstructed path to an electrical connection and thus provides a flexible recharge option. Work by Eruhimov and Meeussen [74] on a PR2 robot developed a system that enables a robot to plug itself into a standard electrical outlet. Plugging in allows a robot to travel long distances in a building and use the nearest outlet when the battery charge is low. They described an algorithm for detection of electrical outlets in images obtained by a monocular camera for calculating 3D coordinates of outlet holes with accuracy high enough for a robot to plug in without visual servoing. During their 13 day continuous run, only 5% of the recharging attempts failed, and 60% of those failures were caused by obstacles in the recharging location, meaning overall success rate of 98%.

However, recharging from power sockets as described in [71, 72, 74] may not always be feasible as the robot needs to keep knowledge of all the available power sockets locations. In addition, power sockets may not be easy to reach due to obstacles and also may be taken up by other electrical devices. There are some commercially available automatic recharge solutions for robots like iRobot's vacuum robot Roomba [75] and Sony's entertainment robot Aibo [59], but these recharge solutions are compatible only with the manufacturer's robots and may not to be compatible with other robot platforms. Robot designers seem to develop their own approaches for recharging mechanisms for their robots. This also makes it challenging to establish a common ground to investigate recharging behaviour of the robot given the different types of robot and their recharging mechanisms in terms of the physical setup and recharging mechanisms used.

Inductive/Wireless Charging The wireless charging station consists of a power supply and two coils for the wireless power transfer, one attached to the docking station and one attached at the bottom of the robot. Since a mechanical plug is not used to establish the electrical connection a high precision alignment docking is not required. However, the better the two coils are aligned, the more power is transferred and higher the efficiency of the recharging system. Compared to direct contact charging, inductive charging efficiency is lower and resistive heating is higher; moreover, due to the large air gap between the primary and secondary windings, contact-less transformers have large leakage inductances, small mutual inductance and low efficiency and the actual charge time can take longer. Compared with plug and socket charging, the primary advantage of the wireless charging approach is that the system can work with no exposed conductors, no interlocks and no connectors, allowing the system to work with far lower risk of electric shock hazards and, avoiding bad contacts between plug and socket, preventing also fire hazard. We describe a few wireless recharging approaches in this section.

Marostica et al. presented a system for the autonomous recharge of the batteries of an electric powered mobile robot, developed in the context of agricultural robotics [76]. The system was composed of a wireless charging station at high power and an autonomous docking algorithm exploiting a camera and a laser range finder. The robot used for this work was the Pioneer 3AT Figure. 2.12 shows the charging system. There was a generator attached to the wall plug that supplies the field coil. The robot mounts the pick-up coil at its bottom that it is attached to a rectifying circuit that supplies the on-board battery charger. The docking was performed in three steps, a) autonomous navigation algorithm to reach a position in front of the docking station. (b) a motion planner for the docking station's approach using datamatrix tag attached over the docking station sensed by the camera. (c) a bearing correction component. The goal of the final step was to reach a very small angle between the robot's bearing direction and the robot-target direction. The overall experimental results claim that about 43%-62% power transfer efficiency was achieved.

Jae-O et al. [77] investigated a wireless power transmission method for a mobile robot. To obtain the maximum efficiency of power transmission, a vision based position control of a transmission antenna was implemented. To recognize the antenna, the Hough Transform and SURF(Speeded-Up Robust Features) methods are used. The pose of the antenna is used to control the mobile robot, refer fig. 2.13a. Some researchers have also investigated continual charging from an electrified floor in the

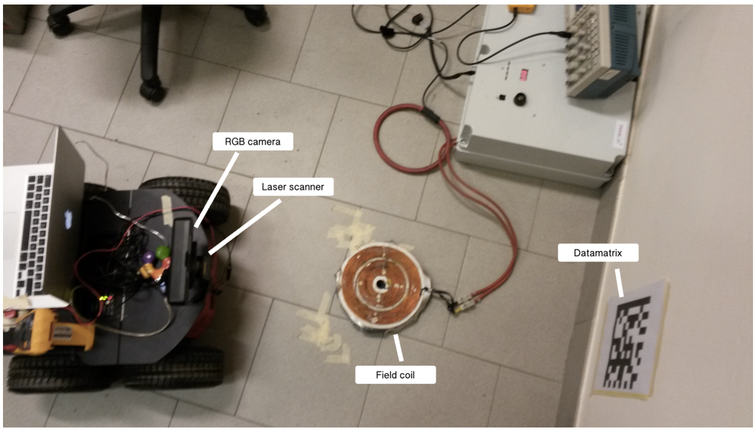
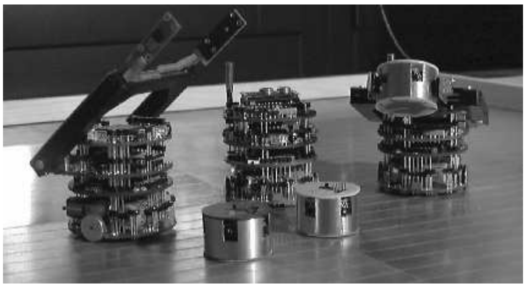


Figure 2.12: The overall system configuration used in the experiments

(a) Mobile Robot and the wireless power system, [77]



(b) Khepra robots charging from electrified floor, [79]

robot arena to provide power to the robots (Khepera Product Literature) [78, 79]. They proposed this as a solution to the energy autonomy problem for experiments with real robots over several hours, but such techniques involve expensive installations and are impractical to use in real settings (refer figure 2.13b). Song et al. [80, 81], proposed the development of an automatic docking system with recharging and a battery replacement process for a surveillance robot was proposed. They suggested an approach where the robot can return to the docking station for recharging operations when the battery is low and replace the battery physically. The battery is automatically exchanged within 30 seconds. So the robot does not need to be turned off for a long duration while replacing the battery. Although this work involves complex mechanical installation for the battery swapping mechanism and may not be feasible to install on existing robot platforms.

Recharging in other applications:

Leading technologist Bill Gates, quoted *"the emergence of the robotics industry, which is developing in much the same way that the computer business did 30 years ago"*[1]. We envisage that the future robots will have similar limitations that computers and other electronic devices have in relation to battery life and recharging. The users

[1]Scientific American, 2007, http://www.scientificamerican.com/article/a-robot-in-every-home/

perception/habits about recharging these devices seems relevant to our work. For example, Banerjee et al. [82] conducted a systematic user study on battery use and recharge behaviour on both laptop computers and mobile phones. They collected data from users of 56 laptops and 10 mobile phones. They reported 3 main findings from their study. The first is that the users frequently recharged their devices with a large percentage of their battery remaining. The second is that the test subjects' charging behaviour was driven by one of two factors: context, such as location and time, or battery levels that are much higher than an empty battery. This finding can be contrasted by the fact that their charging habits were only occasionally driven by a low battery level. The third is that there are significant variations in patterns exhibited by users and particular mobile systems. For instance, laptop users typically use either very little of the battery capacity or almost all of it, whereas the mobile phone users generally use a greater portion of their battery, but rarely run completely out. For each type of device, more than 50% of recharges occur when the battery is more than 50% full. Furthermore, nearly 70% of laptop recharges and nearly 80% of phone recharges occur when the battery is more than 20% full. In summary the users were careful about making sure that they recharged their devices before they ran out of battery and were acting in a very conservative manner. However, a laptop or mobile phone can still be used while charging, while a social mobile robot may not be able to move around while recharging, so its service may be limited. So for social mobile robots to decide at what battery capacity (when it is higher than operational capacity) it needs to initiate a recharge may depend on other factors such as number of users it needs to service, tasks it needs to finish within a time frame etc.

A similar recharge behaviour effect is found with Electronic Vehicles (EV) where the duration of the charging or refuelling process is very important for the consumers' buying decision [83]. A survey by Segal [84], found that few consumers would be willing to accept a charging or refuelling process of at least one hour. The charging process of six hours would discourage consumers from purchasing an Electric Vehicle more than its limited driving range. In terms of users perception about robot recharge, a study by Frennert et al. [85] conducted in Sweden focused on how older people in Sweden imagine the potential role of robots in their lives. The questionnaires in their study involved 36 older adults, with an average age of 77.6 years, most of the respondents used a computer daily (64%). When they were asked to rate, "My Robot would make sure its batteries are always charged", 100% of the respondents agreed to the fact that they would like their robot to be autonomous and make sure that its battery was always charged. Reeves and Nass indicated that people treat computers, television as social actors [86], so we interpret that peoples' expectations about recharge capabilities for future personal social robots may have similar implications as personal electronic devices like phones, laptops or electronic vehicles.

Discussion: Most of the recharging approaches described in this section 2.2.2 involve navigating to the charger where visual markers were used as beacons. Some examples of auto-recharging were given by the "Tortoises" [61], Zelinsky and Taylor [65], Hada and Yuta [63] and Silvermann et al. [68]. These approaches mainly use electric or wireless contact with the charger [77, 76]. Essentially there is trade off between efficiency and accuracy while designing auto-charging mechanism for a robot. A common problem to all these approaches is the robot had to recharge near a wall where the charging connector could be placed (due to health and safety reasons). To the best of our knowledge, the social impact of robot recharging near a wall has not be studied in HRI yet.

The recharging approaches discussed in this section gives an idea of the technical challenges of autonomous recharging. These were carried out on different types of robots and hardware used for recharging mechanisms. Also, most of these approaches were carried out in labs with hardly any level of human interactions and over a short period. It appears that none of them have considered the social context while developing their approach. In other applications like mobile phones and laptops [82], users exhibit conservative recharge habits. In the case of electronic vehicles, customers buying decisions are influenced by battery recharge times [83]. This suggest that users may expect social robots to manage their recharge behaviour carefully. We believe that it is important to investigate the user's perspective on the recharging activity of the robot especially when the robot is being used in a social environment over the long-term. In this thesis we have taken a step forward to investigate the impact of recharge behaviour during HRI.

2.2.3 Power Self Sufficiency

In this section we describe some biologically inspired approaches used to design the recharge behaviour of robots. The long term survival and autonomy of an autonomous system (living or artificial), are governed by energy resources available in the environment and its ability to adapt itself to changing conditions. From an energy autonomy point of view, it is important that a mobile robotic system has awareness of its dynamically changing energy requirements in order to autonomously search and regain its replenished energy from the environment [87]. Adaptiveness of a robotic system allows to tune its behaviour/operations with internal and external system dynamics. For example, the foraging principle as in nature, has been applied in a variety of ways to develop the control and behaviour of a robotic swarm – both individually and collectively. Work has been carried out on a collection of objects scattered around an arena to assemble them in some random or a predefined location [88, 89] and in investigating the collective behaviour of a multi-robotic system [90].

McFarland and Luc Steels at AI lab VUB at Brussels [91], had developed an artificial ecosystem in which robots cooperated in maintaining both their short-term and long-term energy supply. The approach focused on mutualism, which requires co-operation between robots, whereby one robot aids another out of self-interest. According to McFarland, self-sufficiency is an ability of an autonomous system to maintain itself in a viable state for a longer period of time [92]. A self-sufficient robot therefore needs to have the ability to perform the "basic cycle of work", i.e., find fuel and refuel itself [93]. To achieve self-sufficiency, the robot must be able to replenish its energy source independent of human intervention with some appropriate behaviour. The form of the behaviour will depend upon the type of energy source.

Thus a robot may be able to go to a station to recharge batteries, or it may seek sources of light or heat to activate specialised energy gathering apparatus, such as solar cells. The behaviour by which a robot obtains its energy, itself expends energy and uses time that the robot might otherwise use for other purposes (e.g. working). If refuelling took all the robot's time and energy, the robot would have no time or energy for other purposes, thus there is a trade off between refuelling activities and activities designed to please the owner (authors call this the two-resource problem). The authors further introduced the notion of utility from the owner's viewpoint, and performed experiments at AI Laboratory of the VUB, Brussels (refer figure 2.14), with a cue - deficit rule which is related to such utility. The results from their long-term experiments of a simulated autonomous robot, demonstrated that it leads to opportunistic refuelling behaviour in a real robot. However, the authors did not carry out experiments in a social environment to study users perception on recharging behaviour and how it impacts its social acceptance.

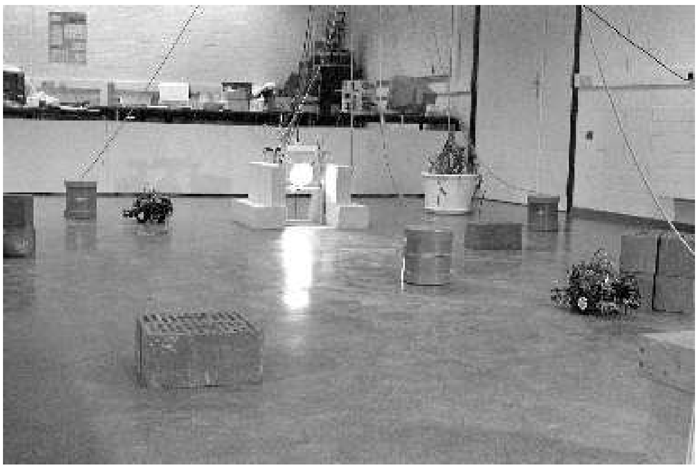


Figure 2.14: A picture of the experimental arena at the VUB with two robots. The recharging station is illuminated (identified by the attached power cables suspended from the ceiling). [93]

Kubo and Melhuish in [94] explore the idea of robot 'trophallaxis', which is a food sharing phenomenon found in nature, that enables a robot to donate an amount of its internal energy reserve to its weaker (having less energy) fellow robots in a swarm. In their model, robots that are engaged in a cleaning task share their energy between each other using a simple collision based mechanism in which after a simple arbitration mechanism, one becomes energy "donor" and the other becomes the energy "recipient". In the results from the simulated run it was noticeable that the "donation" (battery level is larger than the voltage threshold) strategy was better than the "empty call" (battery level is lower than the voltage threshold). The "donation" strategy allows the localised and relatively high density of resources available to only a few robots to be efficiently spread across the robot group. In general this mechanism causes energy to be transferred long before a robot would reach a dangerously low battery level and might be considered a "preventative" strategy. In contrast, the "empty call" mechanism initiates a transfer only when a robot has run into trouble in that its on-board energy value is dangerously low. In this case the advance into potentially energy rich "ground" can be disrupted since a robot cannot move forward if its neighbour is "calling for help". The results from simulation indicated that, building an energy transfer capability into a collective of autonomous robot might prove worthwhile and advantageous. Although, such energy sharing approaches will require a group of robots to be employed at the same time (not always feasible) in a social environment with complex mechanisms to share energy. Also the authors did not appear to consider the time required to transfer energy from one robot to another to switch roles ("donor", "recipient").

Other approaches have looked at extending the operational time and improving the energy autonomy of individual autonomous modules. In a robotic swarm the authors applied different techniques that use either, threshold mechanisms which are based on the battery voltage level [18], activation variables [95] or time [96] to determine an appropriate action for a robot. Michaud and Robichaud [96] explored an approach that allows robots to predict and reason about their energy capabilities, as individuals and as a group. Their approach allows robots to determine when to recharge, when to change their activity level and how long they should recharge while sharing a charging station. They highlighted the potential issues that arise in an arena with limited energy resources, e.g., *"when is it appropriate for a robot to recharge", "how long should the robot recharge itself", "what can be done to preserve energy"*, however, their approach does not resolve all issues. In their approach, the operational time estimated from the battery voltage value is used to determine the appropriate "time" to recharge a robot. Validation of their work is carried out in simulation to demonstrate the versatility of the approach for different numbers of robots and power sources. Their algorithm for making each robot accomplish tasks and share power sources in a group environment is illustrated by the state diagram shown in Figure. 2.15

Link A represents the conditions for which a robot will start searching for a power

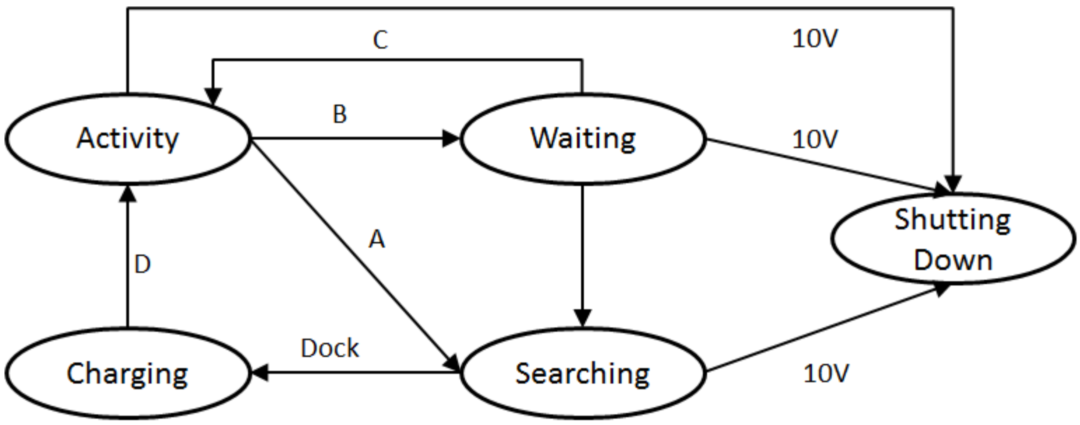


Figure 2.15: State diagram of the approach [96], it represents the decision process followed by each robot.

source, Link B monitors similar conditions to link A, but to determine when to go from the Activity mode to the Waiting mode. Link C allows a robot in the Waiting mode to become active again because it anticipates that it can go back into the Activity mode without compromising the survival of the group. Finally, link D monitors conditions like no energy sensed at the power source or maximum energy reached for the batteries to make a charging robot leave a power source. For the group to survive, the amount of time spent charging by the group must be lower or equal to the amount of time spent in activity or waiting: otherwise robots will be shutting down (battery voltage <= 10V). The authors carried out this work in simulations and not in an actual physical environmental and the underlying challenges with recharging and having humans in the interaction loop did not appear to have been investigated. It is important to consider the real challenges of having a humans as an interaction partner while the robot is providing services to users and how it impacts the social perception of the robot.

Kernbach et al. in [97] presented a kinetic model of swarm foraging to maintain energy homoeostasis in an arena with fixed recharge stations. Energy homoeostasis is a means of keeping the energy flow balance/equivalent among the individuals in a robotic swarm. Their model uses the time spent by the robots during working, searching, waiting, and recharging, to measure the energy efficiency of the swarm. The model assumes the charging and discharging time of the robotic modules to be the same as charging and discharging currents of the robot. This implies, while operating in the environment, one half of the swarm population keeps itself busy in performing the assigned task and the other half is docked to the recharge stations. Another approach to recharging was proposed in [98], where the robots in the team can physically exchange batteries. Their approach is inspired by the swarm behaviours of honey-bees and forms a strategy game: the honey-bee is fairly collecting food to common nest while the strategy game imagines a society in which “farmers” are working to support energy requirements of “solders” and “fighting units”. They focused on energy to prove that a multi-robot system can have long-life survival if they can carry and share energy with other robots using social rules. This system is different with respect to the rate of energy transfer between team members, though it requires a high degree of synchronisation to be successful. The idea of using robot swarms to serve each others energy needs is very challenging to achieve in a social environment, also to deploy multiple robots in a social environment can be impractical due to the high costs of robots.

To make advances in energy autonomy, robots may need to extract energy from the environment [99]. In many ways robots will face the same problems as animals. Examples include the Mars rover Sojourner [100]. Sojourner does not need to look for its energy sources because its solar panels automatically relay power as soon as the sunlight hits them (non-chargeable batteries were used as a back- up) and is a well-known representation of robots that survive from their environment. Recently the Rosetta mission in November 2014, where the Philae robot lander sitting on a Comet ran out of power after an attempt to nudge it into better sunlight apparently came too late to charge its batteries and keep systems up and running. However, Philae came nearer to the Sun later this year to get enough solar illumination to wake up the lander and re-establish communication[2]. So depending on just one energy source can be risky in some cases. However, in social environments like homes, workplace, public spaces, recharging from solar energy can be impractical and time consuming for a full recharge of batteries.

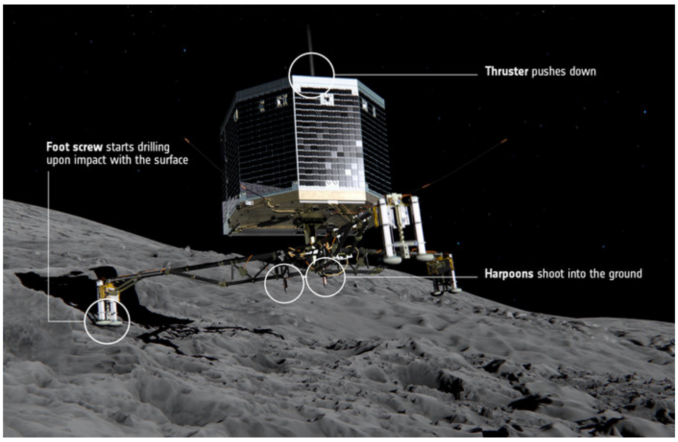


Figure 2.16: Philae lands on the comet

The SlugBot [101], tried to establish a cycle of catching slugs and using them to generate power via a on-site bio-gas generator (figure 2.17). When the on-board slug container is full, or when the robot needs power, or when it appears that more energy will be used in hunting than is expected to be gained from it, the robot will return to

[2]http://www.esa.int/Our_Activities/Space_Science/Rosetta

the bio-gas fermenter, where it will deposit any slugs and perhaps recharge itself. In contrast with its predecessor Slugbot, the team at Bristol Robotics Laboratory, later developed two robots namely EcoBot-I and EcoBot-II. EcoBot I, was the first robot in the world to acquire all its onboard power from microbial fuel cell, MFCs (i.e. it carried no batteries), employed E. coli and was fed with sugar, this was a proof-of-concept sugar-eating robot, that follows the light. Later they worked on EcoBot II [102] where they investigated raw foodstuffs such as flies or rotten apples for energy. They explored the feasibility of extracting electrons from biological substrates (insects, fruits) using microbes in mediator-less Microbial Fuel Cells (MFC) to power small robots. Furthermore, they showed that it is possible to use oxygen as the electron-acceptor of the MFC to work with air. EcoBot-II could successfully perform token tasks including phototaxis, temperature sensing and data transmission. A functional performance has been shown to continue over a period of twelve days with low system efficiency, for the closed system MFCs.

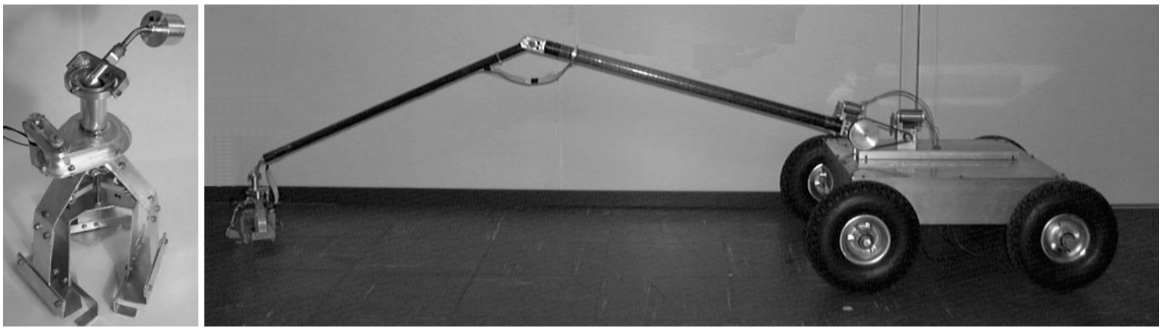


Figure 2.17: Prototype three fingered gripper with wiper blades and compliance gimbal (left), and the arm and gripper system mounted on a turn table (right) [101].

What makes these approaches of extracting energy from slugs [101], sugar, raw foodstuff [102] etc. particularly challenging is that, even with unlimited supplies of slugs, sugar, foodstuff, their system will at best be on the borderline of survivability due to the energy acquired from these sources in comparison to energy required to sustain an operating system. Moreover, since the scheme used for energy recovery is likely to be at least an order of magnitude worse than any biological system, the performance requirements are likely to be even more severe than those which an animal living entirely on slugs would face.

Discussion: In this section 2.2.3 we looked at approaches based on concepts from nature and applying them to the design of recharging systems for robots. Power autonomy is important for mobile robots for long term survival and to achieve true autonomy. Work by McFarland [93] motivated the idea of self-sufficiency, to perform the "basic cycle of work", i.e., find fuel and refuel itself and manage the trade off between refuelling activities and activities designed to please the owner. Kubo and Melhuish [94], Michaud and Robichaud[96] explored the idea of battery sharing between robot teams. While Kernbach et. al. in [97] presented an approach to maintain energy homoeostasis as a means of keeping the energy flow balance/equivalent among the individuals in a robotic swarm. These approaches tried to manage each individual's as well as groups power needs in a collaborative manner. However, these approaches were not conducted in real social environments where the robots may require to interact with human subjects. Sojourner [100] and work by SlugBot [101], EcoBots [102] explored the idea of robots extracting energy from the environment. Although the idea of power self-sufficiency sounds interesting, the approaches discussed in this section were not very energy efficient and more impractical to meet the power demands of a robot in a realistic case. It is important to note that the work described in this section 2.2.3 was carried out in labs with hardly any level of human robot social interaction. So how recharging behaviour of robots might be impacted when you put a human in the loop was not the focus of their research.

2.3 Long-term Interaction

We see two main challenges to long-term HRI; firstly the technical challenges of building systems that can operate in sustainable manner and secondly the social challenge to keep the user engaged and motivated to interact with the robot inspite of its inevitable errors and limitations. We present some existing work on long-term human-robot interaction studies focusing on the two main challenges (technical and social) in this section. We describe some work in different social contexts for example workplaces, public places, therapy, education and domestic environments. In order to narrow down the discussion to fit our research goals, we focus on long-term studies centred around social mobile robots in this section. We define mobile robots as physical embodiments that can physically move and require batteries as their power source.

2.3.1 Workplaces

In the context of social mobile robots in workplace environment, Severinson-Eklundh et al. reported perhaps one of the first long-term studies in a real-world setting involving a social robot Cero [103, 104]. The Cero robot had a simple, fetch-and-carry functionality. The robotic platform was based on a Nomadic Super Scout platform with 16 sonar sensors to support navigation, graphical user interface (GUI), a mobile interface on a Personal Digital Assistant (PDA), and an animated character on the robot platform to support the understanding of a spoken natural language interface, refer Figure. 2.18a. The goal of the study was to investigate social aspects of the interaction with a fetch-and-carry to assist a partly motion-impaired user with the transportation of light objects in an office environment. The robot was evaluated in a long-term usage study over three months, with a single target user, a female academic with a walking disability. The overall conclusion of the study was, that addressing only a primary user in service robotics is unsatisfactory. They concluded that the focus should be on the setting, activities and social interactions of the group of people where the robot is to be used. As shown in their study the secondary users did not know how to deal with the robot when they encountered it. This is particularly important when a robot is used as a shared device in the same physical space and will have to deal with meeting the demands of multiple users in a realistic scenario.

Robots deployed in a workplace environment operating over a long-term period may face challenges with localisation in changing environments. We describe two approaches to localisation for long-term navigation, one focused on developing technical capabilities [105] and other focused on a social solution [106]. In the first approach Krajnik et al. [105] presented a new approach for topological localisation that makes use of information about the dynamics of the environment to improve the localisation process. They proposed a spatio-temporal world model which is able to predict environmental changes in time using observations composed of image and point clouds obtained using an RGB-D sensor, allowing the robot to improve its localisation capabilities during long-term operations. In their study a mobile robot autonomously patrolled an office environment for a period of one week, during which the robot built two types of spatio-temporal models of eight office locations with different dynamics. The results showed that the experience learned during one week is applicable for topological localisation even after a gap of three months by showing that the localisation error rate is significantly lower compared to static environment representations.

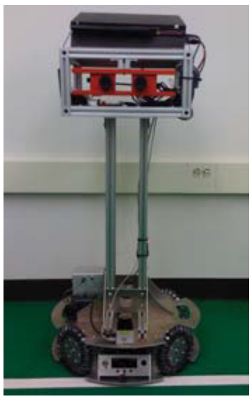
The second approach by Biswas and Veloso [106] developed collaborative robots, CoBots (figure 2.18c), which have been autonomously traversing multi-floor buildings in CMU. The authors' main goal was long-term autonomy for indoor service mobile robots with an ability for them to be deployed indefinitely while they perform tasks in an evolving environment. CoBot accepted requests from users, autonomously navigated between floors of the building, and asked for help when needed in a symbiotic relationship with the humans in its environment. Their results show that CoBot while asking for help can reduce localisation uncertainty as well as the number of replanning steps the robot must take compared to autonomous navigation. As a result, the robot backtracked less and took less time to navigate without asking many questions (50% reduction in the replan steps, and a 9% reduction in navigation time). Social solutions to hard technical problems of localisation for robots can also prove effective in some cases.

2.3.2 Public Spaces

In public spaces, Tomatis et al. [107] presented a study to maximise the autonomy and interactivity of the mobile platform while ensuring high robustness, security and performance. The authors developed an interactive mobile robot that can operate in human environments and interacts with them by talking to, and looking at them, showing them icons and asking them to answer its questions. In their paper they presented and analysed the number and type of robot failures. In public spaces, Stubbs et al. [108] examined how people's cognitive model of a robot changes over time. The target robot was PER (Personal Exploration Rover), a robot designed as a tool to educate the public about certain aspects of NASA's Mars Exploration Rover (MER) mission (figure 2.18b). The subjects were museum employees who interacted with PER on a daily basis for a period of 6 months. The study consisted of interviews of 11 museum employees at different stages of their relationship with the robot. Some open-ended interviews were conducted once before the PER exhibit had been installed, one to two weeks after the exhibit had been installed, one and a half months after installation, and three and a half months after installation. Over a period of time employees became more familiar with the PER, and they tended to focus on the robot's actual successes and failures rather than what it was supposed to be capable of achieving. This indicates that limitations and failures in robotic services can be negatively perceived especially over long-term.

(a) Cero Robot, [103]

(b) Personal Exploration Rover [108]



(c) The CoBot Visitor-Companion Robot [106]

Figure 2.18: Robots in Public spaces

Work by Nourbakhsh [4], what can be called as one of the most successful long-term run of an autonomous robot Sage, a robot tour guide in a museum. SAGE gave tours in the Carnegie Museum of Natural History, its goal was to provide educational content to museum visitors in order to augment their museum experience. The robot had very simple obstacle avoidance and navigation routines and used 2D/3D markers placed in the museum for localisation. Sage provided 174 days of service to the museum, with only a few breakdowns (the paper did not specify how many breakdowns and why) and totally unsupervised operation. The robot had eight hours of autonomy and could measure the charging and discharging current of its batteries: as well as their voltage levels. This information was used to determine the batteries' state relative to a discharge curve (which is not provided in the paper). The robot had a mean time of 224 hours (9 days) before failure, including the time the robot was recharging (which is not described in the paper) and it was probably not working when the museum was closed. The robot could recharge itself when it returned to its base and could dock into an unmodified plug. However, it used very visible artificial markers to identify its base and to recharge its battery. The overall power consumption of the entire Sage robot used about 300 watts during active operation. On-board battery capacity was designed to allow for eight hours of activity with 25% charge remaining, refer to Figure 2.19. Having a battery capacity that can operate for a working day/shift (8 hours) can prove effective so that the robot is available for the maximum duration it is expected to provide service. However, this would also require installation of more or bigger batteries on the robot increasing the overall weight of the robot, which may result in more power consumed during navigation.

Figure 2.19: Sage robot in Museum [4]

Kanda et al. [109] evaluated a Robovie robot in a shopping mall. In this study, the robot was programmed with a set of behaviours particularly relevant to a shopping mall environment. Apart from building rapport with users by identifying them using RFID tags, employing self-disclosure mechanisms and adjusting the dialogues based on the previous dialogue history with each user, Robovie was also capable of offering directions and advertising specific shops and services of the mall, refer Figure. 2.20a. The long-term study had 162 participants, however only 72 of them interacted with the robot more than once and only 23 participants interacted with the robot more than 5 times. The authors interpret that this effect may have been caused by the continuous presence of many people (visitors of the shopping mall but not official participants of the study) around the robot. Due to the large queues, participants hesitated before deciding to interact with the robot. The questionnaires mailed to the study participants (even the ones who only interacted with the robot once) suggested that their perception of the interaction was positive, not only in terms of perceived familiarity, intelligence and interest towards the robot, but also regarding intention of use and adequacy of the route guidance behaviours. Moreover, repeated visitors provided significantly higher rankings in the questionnaire. In addition to these results, the study also concluded that people's shopping behaviour was influenced by the robot's suggestions. However their work did not mention the charging characteristics of the robot, also due to the large sample size of participants, each participant may have got less one-to-one time to interact with the robot. Having a more intimate interaction experience with a social robot allows more in depth insights into the user's perspective on the robot.

(a) Shopping Mall Robot Robovie, [109]

(b) Robovie robot at School [110]

(c) QRIO robot interacting with toddlers, [111]

Figure 2.20: Robots in Malls and Schools

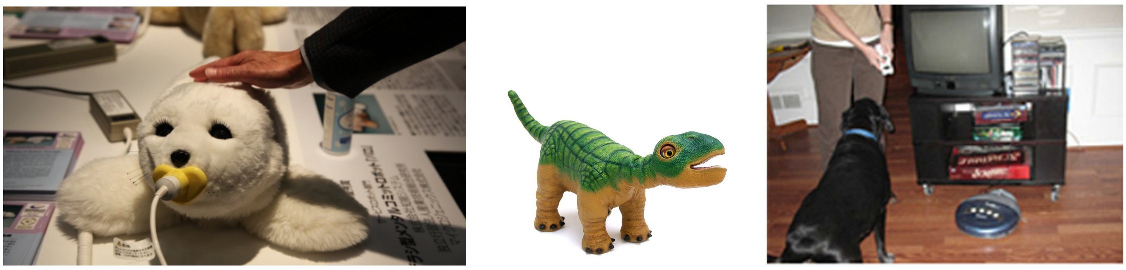
2.3.3 Education and Therapy

Kanda et al. [110] also reported a practical and long-term experiment with autonomous humanoid robots in an educational environment. Students in an elementary school interacted with the robots over 18 days. The robot, "Robovie" used RFID tags to identify individuals and adapt its behaviours to them. In this experiment, the robot spoke in English with Japanese students, refer figure 2.20b. The study revealed that the robots failed to keep the children's interest after the first week, mainly because the first interaction created high expectations in the children. However, children who kept interacting with the robots after the first week improved their English Skills. They also found that, very often, children interacted with the robots together with their group of friends.

These results inspired some changes to the system where Robovie's capabilities were extended to better support long-term interaction with children [112]. The new capabilities include a pseudo-development mechanism (the more a child interacts with the robot, the more different behaviours are produced by the robot to that child). Self-disclosure behaviours were added (e.g., the robot may reveal its favourite baseball player). This enhanced version of Robovie interacted with children in Japanese in their classroom for 2 months (32 actual experimental days). In contrast to the results obtained in the previous experiment, Robovie was capable of engaging children after the second week (although with a slight decay), which the authors attribute to the new capabilities implemented in the robot. The children's motivations for interacting with the robot were also studied. Most children answered that their main motivation was to become friends with the robot. Both these studies by Kanda et al. [112, 110] highlighted that novelty effects fade over time. Children's interest and engagement decreased over time. They did not appear to mention recharging of their robots during the studies. So how recharging behaviour can impact interaction and perceptions of children does not appear to be the focus of their research.

Tanaka et al. [111] reported a longitudinal study where a robot QRIO interacted with toddlers in a day care centre for 45 sessions of 45 to 60 minutes each. The sessions ended when the robot sensed low battery power, at which point it laid down and assumed a sleeping posture. Thus the authors adapted the battery limitation into the social interaction. The authors did not give any details about the recharging behaviour of the robot assuming a sleeping posture in their paper. In their study QRIO would display several behaviours including choreographed dance sequences and mimicking some of the children's movements (Figure. 2.20c). Moreover, when introducing two inanimate toys in the environment (a teddy bear and a toy very similar to QRIO), QRIO was still the most hugged by the children followed by the toy that looked like the robot. The results of this study suggest that toddlers progressively started treating the robot as a peer rather than as a toy, as they exhibited an extensive number of care-taking behaviours towards the robot. Blending the battery limitation of the robot into the social context seems to be a sensible approach especially with young toddlers as they can associate more with the needs of the robot playing with them. However, such an approach with adults may be perceived differently in regards to its social acceptance and it would require further studies to validate this approach for adults.

In robot therapy, Wada and Shibata [113], [114] developed the robot Paro, a seal-shaped robot specifically designed for therapeutic purposes. The robot has five senses, and uses them to perceive touch, light, sound, temperature and posture. The robot is also programmed to behave as much as possible like a real animal, waking up a little dazed and confused, enjoying cuddles and pats, complaining if it wants attention or 'food' (a battery charge), and reacting with fear and anger to being hit. Paro's battery can be recharged by plugging in a pacifier in its mouth (figure 2.21a) so the recharge is designed to blend into the social context of its use. In their study, two therapeutic seal robots were introduced and used for over 9 hours every day to interact with residents of care house. After one month, the results for 12 subjects indicated that PARO strengthened the social ties among the residents of the care house and that most residents established moderate or strong ties with the robot (e.g., greeting Paro when they passed by). Also, results of urinary tests showed that the reactions of the subjects' vital organs to stress improved after the introduction of the robots. Furthermore, the results of the case studies indicate that the residents' social interaction with each other increased through interaction with the seal robots. Although, the overall results from their study were positive, the participants' perception during recharging was not investigated by the authors.



(a) Paro's pacifier is also its battery charger [113]

(b) Pleo robot, [115]

(c) Roomba robot at home, [116]

Figure 2.21: Robots in therapy and homes

2.3.4 Domestic Environments

In domestic environments, Fernaeus et al. [115] reported a study with Pleo, a robotic toy dinosaur (Figure. 2.21b). Six families took a Pleo robot home for 2 to 10 months (each family decided for how long they wanted to keep the robot). One of the goals of the study was to obtain a better understanding of the design challenges involved in developing advanced interactive toys for everyday setting. Most families were interviewed twice after having Pleo in their homes. The feedback from the participants was that they found recharging Pleo became a time-consuming activity. The fact that Pleo allowed only one hour of play but required four hours to recharge frustrated both the adult and child participants. Participants did not like the fact that there was no way of telling when the robot was going to run out of battery, and that you actually need to remove the battery from Pleo to recharge it. When reflecting upon this, several parents compared Pleo with regular home appliances and how even a simple electronic toothbrush can recharge itself without having to remove the battery. The authors received many suggestions about how this could be improved and made more “integrated” into playing with Pleo. For instance, parents suggested that recharging could be done simply by putting it in a special bed, similarly to the Roomba vacuum cleaning robot which has a docking station for recharging. That the battery needs to be removed from Pleo also became a serious obstacle for play in another way. The fact that Pleo froze and became unpleasant to handle and play with when it was switched off or when the batteries had run out, disturbed the children in their play experience. Moreover, as an electronic device, this kind of maintenance was difficult for the families to accept. This is one of the very few studies in HRI where participants feedback on recharging was collected. However, the robot used during the study was smaller in size (smaller battery capacity) and did not have to move around much. A larger mobile robot which can navigate and interact with users in a social environment will require a larger battery capacity and may magnify the negative perception of the robot. We therefore investigated the perception about robot’s recharge with a larger mobile robot in a social environment in this thesis.

A longitudinal field study was carried out by Sung et al. [117, 118] with 30 households over a period of 6 months using a commercially available vacuum cleaning robot Roomba (Figure. 2.21c). An experimenter visited each household five times during the six-month period. The first visit took place a week before Roomba was introduced, the second visit when families had unpacked the robot and used it for the first time, and the other three visits took place respectively, two weeks, two months and six months after Roomba was introduced. During the visits, interviews were conducted, and in addition drawings, probing techniques and check-lists of the activities they performed with Roomba were collected in order to understand people’s routines and acceptance of the robot. Participants were also encouraged to report their experiences with the robot via e-mail. The authors argue that two months is long enough to observe stable interactions between robots and households in a domestic environment. They also found that the combination of several data collection methods is extremely useful for capturing people’s routines and interaction with the robot, especially in a domestic environment. From their study experience they also established a long-term experimental framework [116]. This framework includes four different temporal steps that contain key interaction patterns experienced while households were accepting the robot: pre-adoption, adoption, adaptation and use and retention. This methodology of the combining several data collection methods was also adopted during the analysis of studies performed in this thesis.

Another important aspect that constrained this study [118], was the location of electrical sockets, as the robot’s charging station needs to be plugged in so that the robot could automatically go back to it. In three homes there was a lack of electrical sockets in the living room and in two of them, the height of the sockets meant that the charging station could not be placed on the ground because the cable was too short. This was clearly impractical and it made it difficult to use the robot in its intended way because it constrained its autonomy. The authors reported that, in the end, this negative experience hindered people in integrating the robot in their cleaning routine. Some people had difficulties with having the robot's charging station visible in a prominent open social space, such as the living room. People did not want to have either the robot or its charging station visible in the living room. Robots and humans sharing the physical same space, need to adapt to each others technical and social requirements. Also Roomba robot hardly has any social interaction capabilities and is much smaller (crawls along the floor) than other social mobile robot platforms used in research for example Peoplebot robot. We anticipate that the social implications with bigger mobile robots and its recharge activities require further investigation.

2.3.5 Mobility

From the above long-term studies we interpret that one of the main limitation caused by the robot while it is recharging is its ability to move and perform tasks. The movement of an object or organism regardless of its appearance is a powerful interaction medium, humans, like most animals, are highly sensitive to perceived motion [119]. In human-human interactions, proxemic behaviour and interpersonal spacing is found to be profoundly communicative. Hall [120] showed that proxemic behaviour in humans indicate relationship, mutual attitude and relative status to each other. Burgoon and Walther [121] suggest that proxemics behaviour can dramatically alter the nature of our relationships, and that changes in how we feel or reason about the people we interact with depend on responses to such changes in proxemics. Given the strong evidence in human-human interaction being dependent on this spatial interaction dimension, it seems that even for robots the ability to move may influence the user's perception of the robot [122]. The ability for a social robot to physically move around to perform tasks such as communicative or transporting objects makes them different from other electronic appliances. There are important advantages for a social robot in being able to move in a shared space with human users [104].

A particular study by Syrdal et al. [58], examined the role of spatial behaviours in building human-robot relationships in a long-term HRI study. A group of 8 participants, interacted with an artificial agent using different movement capabilities over a period of one and a half months. The two robots used in their study had similar interactional and expressive capabilities, but only one robot was capable of moving, the other was stationary, refer figure 2.22. Both robots were capable of performing most socially assistive tasks, such as reminders and providing information but only the stationary robot could be used for communicating with another person via Skype, while the mobile robot could follow and guide the participant when walking around the robot house. Participants interacted with both the robots through touch-screens for

Figure 2.22: Living Room Area with mobile robot in the front and a stationary robot in the back.

approximately the same amount of time. Participants interacted with the agent in its robot embodiments in 9 sessions, two sessions a week, and filled in the questionnaire at the beginning of the 10th, debriefing session. The results reported participants feeling closer to the robot embodiment capable of physical movement and rating it as more likeable, even though the two robots had very similar interactional capabilities.

A second analysis of a long-term, continuous human-robot cohabitation experiment by H. Lehmann et al. [30] (previously reported in section 2.1) involved two professional artists living in a Robot house for a period of one week. The robot house at University of Hertfordshire is dedicated to HRI research in a realistic, domestic environment. Another interesting finding in this study was that the users would prefer to have the robot around them in the living room instead of having it come to them to inform or remind them, then move away to charging station between interactions. These results on mobility of the robot [30, 58] suggests that interactions that involve moving in shared physical space and robot's spatial behaviour, do play a role in building of a relationship between a social robot and a human user.

Discussion: The studies describe in this section provide valuable insights into long-term interactions with robots in different social settings. In workplace environments, 2.3.1, the study on the social office robot Cero [103] with a single user concluded that addressing only a single user may not be the best practice and that the focus should be on the setting, activities and social interactions of the group of people where the robot is to be used. This is particularly important when a robot is used as a shared device in the same physical space and will have to deal with meeting the demands of multiple users in a realistic scenario. In public spaces, 2.3.2, Tomatis et al. [107] and Nourbakhsh [4] provided successful examples of long-term interaction in public spaces with a high degree of robustness and performance. Robustness is vital for long-term interaction with robots as failures will be picked up and criticised by the users as reported by Stubbs et al. [108].

Long-term studies by Stubbs [108], Nourbakhsh [4] and Kanda [109] highlighted that novelty effects fade over time and the user's interest and engagement decreased over time. However, none of these studies investigated the impact of recharging behaviour of the robot. How recharging is perceived by users in long-term interaction context still appears to be an open question. In domestic environments, 2.3.4, Fernaeus et al. [115] reported study with Pleo, a robotic toy dinosaur, the families that interacted with Pleo reported issues with the battery recharge and how this severely affected their perception of the robot. The issues with battery maintenance were difficult for the families to accept. Families also made many suggestions about how the recharge behaviour could be integrated into playing with Pleo. On the other hand, in the study with Paro seal robot, Wada and Shibata [113] provided the robot with a pacifier charger which the users could to plug into the mouth of the robot, thereby giving an impression to the users that they have something to take care of. Similarly, Tanaka et al. [111] incorporated a sleeping behaviour for their robot QRIO while interacting with the toddlers and when the battery was low. From the studies on Paro and QRIO robots, although they did not report the impact of the recharge behaviour on the users in their study, it appears that integrating the battery recharge behaviour into social interaction may perhaps be more acceptable to the user and give an impression of life like characteristics to the user.

Sung et al. [117] proposed approaches to conducting long-term studies in domestic environments and also established a long-term experimental framework [116]. Domestic environments require different means of investigation from public spaces such as hospitals and schools due to the private nature of domestic routines. The study reported methodological challenges in understanding households' usage patterns and recommended that some interventions such as logging may be necessary to mine natural interactions. For the interventions that require participants carrying out tasks without the interviewer's presence, the authors proposed the use of activities that fit into users routines (e.g., emailing photos rather than keeping a scrapbook). Fink et al. [118], reported feedback from the participants that the recharging mechanism of roomba was sometimes impractical and this hindered people in integrating the robot in their social as well as cleaning routine. Careful consideration of both the social and technical requirements is necessary for robots in domestic environments to be viable and socially acceptable.

The study by Syrdal et al. [58] suggests that the role of the robot's ability to move and share the physical space with the user has an impact on the formation of human-robot relationships. While the recharge behaviour is active, the mobile social robot may be prevented from movement and fixed in a particular location, this may impact human-robot relationships in the long-term. So movement of the robot is important and there is a greater need of some sort of social behaviour to manage user expectations while the robot is incapable of movement while recharging.

Although some long-term studies reported in this section may not be directly relevant to recharging issues, they provide some useful insights on the methodology used to carry out long-term studies. For example Kanda [109] on data collection and Sung et al. [116] suggested a long-term experimental framework. While these long-term studies highlight different issues that arise during long-term interactions, they also have different social environment (domestic vs public) and users to serve.

2.4 Conclusion

In this chapter we reported some work relevant to the aspect of recharging for social mobile robots. We summarise some key findings from the existing work related to this thesis.

- **Social Handling:** Social handling and transparency appear to be important to mitigate the negative effects caused due to the limitations and mistakes from the robot. Using non-verbal transparency strategies Lehmann et al. [30], Koay et al. [31] and verbal transparency strategies such as apology, Jost [33], and Lee [15] reported positive impact on social acceptance of the robot. Paepcke & Takayama [13] and Lohse [40] showed that users' expectations can be influenced by the robot's behaviour. When the perceptions of an agent exceed users' expectations, it can ease their social acceptance, as shown by Komatsu et al. [14]. These findings highlight the importance of social mitigation strategies in HRI, how they might be used during robot's recharge behaviour is still an open question. Hence, we investigated an approach based on verbal strategies in this thesis.

- **Autonomous Recharging:** Autonomous recharging involves 3 main steps; finding the charger, approaching the charging station and plugging into the charger. Some examples of auto-recharging were provided in section 2.2.2 by the "Tortoises" [61], Zelinsky and Taylor [65], Hada and Yuta [63] and Silvermann et al. [68]. There is a trade off between efficiency and accuracy when designing auto-charging mechanisms for a robot. However, there seems to be a strong argument for having a direct charging mechanism as this significantly reduces the recharge time. In this thesis we developed an approach using direct charging following the insights from existing work.

- **Battery Issues:** The limited life span of batteries and long recharge times also encourages the idea of having some sort of behaviour produced by the robot so that it is not completely useless during recharge(section 2.2.1). We tried to address this issue in this thesis, with an approach based on verbal behaviour. In our approach, the robot can perform verbal tasks in a socially intelligent manner.

- **Autonomy:** Robots need to be self-sufficient in order to achieve true autonomy. To achieve self-sufficiency, the robot must be able to replenish its energy source independent of human intervention with some appropriate behaviour. There is a trade off between refuelling activities and tasks designed to please the owner, McFarland [93] (section 2.2.3). In this thesis we investigated the social impact of recharging and the robot was not able to perform tasks to validated our research goals.

- **Robustness:** Robustness is a very critical aspect while developing mobile social robots operating over a long-term period given the uncertainty of dealing with real social environments. People tend to pick upon issues with failures and limitations of the robots quite critically [8]. Tomatis et al. [107], and Nourbakhsh [4] provided examples with robust autonomous robotic systems that lived in social environment for a long-term period and provided service to users. We developed robust navigation and recharging mechanism for our robot in this thesis.

- **Long-term interaction:** Long-term studies with the Pleo robot (Fernaeus et al. [115]), reported issues with limited battery life which negatively influenced their social acceptance. However, Tanaka et al. [111] and Wada and Shibata [113], implemented the recharge behaviour as a part of social interaction to manage the limitations of the robot with limited battery life. Other long-term studies provided some useful insights on the methodology used to carry out long-term studies for example Kanda [109] on data collection and Sung et al. [116] suggested a long-term experimental framework (Section2.3). We have considered these previous work on long-term interaction to plan our approach.

- **Mobility:** Mobility can have an impact on the robot's social acceptance as shown by Syrdal et al. [58]. Lindner and Eschenbach [35] proposed an idea on social placement for a mobile robot taking into account affordances while recharging (section 2.3.5). While the recharge behaviour is active the robot can become immobile hence the aspect of mobility was investigated in this thesis.

Existing work reported in this chapter had different research goals to those of this thesis and were conducted in a variety of social environments for example in workplaces, public places, therapy, education and domestic environments. Some studies directly pointed to the issues caused by a robot's recharge behaviour and how it impacted its social acceptance. The important and fundamental issue of robot's recharge behaviour does not appear to be widely addressed in a socially intelligent manner. This strengthened our research aims and makes this a valid and interesting avenue for further investigation. We have taken some useful insights obtained from this chapter summarised in this Section 2.4 to design our approach presented in the next chapter.

Chapter 3

Approach

This chapter describes the approach adopted to develop the scenario to investigate our research questions. In order to design our scenario, we first wanted to understand the scenario requirements and the user activities in the workplace environment in which we planned to conduct our research. We have taken some useful insights gained from the previous Chapter 2 on existing work to design our approach. We first describe our approach to scenario design in Section 3.2. Then we describe our research methodology in order to carry out the proposed research in Section 3.4. We then discuss how we designed the robot hardware in order to meet the scenario requirements and perform the designed tasks in the workplace environment (Section 3.5). We also then describe the capabilities developed for the robot, for example navigation (Section 3.6), auto-recharge (Section 3.7), user monitoring (Section 3.8), and proxemic adaptation (Section 3.9). Followed by description of the architecture used in our scenario in Section 3.10. Finally summary of our approach in Section 3.11.

3.1 Introduction

In the previous Chapter 2 we discussed long-term experiments carried out in a variety of social environments. Existing work in social robotics, in practice has nearly always considered short life-time systems. These robots interact for at most a few hours with people and usually just once for any particular person involved in a given study [23]. Exceptions to this have considered very rudimentary long-life capabilities such as the ability for a robot to autonomously recharge itself, or repeated (but still short-term) exposures of people to a robot [3]. These early studies have shown that the novelty effect of robots and characters quickly wears out and that people change their attitudes and preferences towards the robots over time [111, 110]. It appears that very few studies have investigated in depth the effects of people's interaction with such systems over extensive periods of time where the functional and social skills of the robot are thoroughly tested. We argue that if robots are to become true personalised companions, then the functional and social requirements, as well as the consequences must be understood and addressed in order to make such future systems acceptable and usable. In this thesis we wanted to study how a robot's recharge behaviour impacts on people's perceptions and interactions. Our work has addressed these issues from a technical and social perspective to study human-robot interaction "in the wild" and to develop and evaluate the technology required to provide socially intelligent recharge behaviour.

3.2 Scenario Design

In order to investigate our research questions (Chapter 1 Section 1.4), to study the impact of recharge behaviour during long-term human-robot interaction, it was necessary to have a scenario within which to conduct this work. This research was carried out in the context of a scenario that was part of the EU project LIREC (LIving with Robots and IntEractive Companions[1]. The LIREC project aimed to create interactive, emotionally intelligent companions, capable of establishing long-term relationships with humans in social environments. The "Spirit of the Building" showcase at Heriot-Watt University, Edinburgh, aimed to produce a social helper robot that could act as a "Team Buddy"; an office assistant within an office (a room located in the Computer science department at Heriot-Watt University) inhabited by a group of people who work at their allocated desks.

This scenario was tailored for adults; it involves the robot interacting and performing tasks with one user at a time in a group of at most five people. The LIREC project anticipated that our target user group would be adults who can interact with a robot without having much technical background. The project envisaged that a workplace/office environment would be an appropriate scenario to study the long-term effects in an ecologically valid setting. In this chapter and following chapters of this thesis we state clearly which part of the reported work was performed by the LIREC project team and which part was developed for this thesis.

To better understand how people will interact, use and perceive the service a workplace robot in a long-term context, it was important that the robot embodiment be placed in the same physical space as the users over a long-term period. Sharing the same physical space with the robot would allow the users to closely experience the patterns and habits of the robot's recharge behaviour and its service. Such a scenario involves technical challenges and privacy issues with the user, so that domestic, educational establishments, care homes etc. were not well suited to carry out our research. Hence, we anticipated that the LIREC "Team Buddy" scenario would be appropriate to conduct our research which also has a high ecological validity (ap-

[1] www.lirec.eu

proximating real-world settings) [123]. We thereby, adapted the LIREC scenario to study the effects and users' perceptions of the robot's recharge behaviour. Table 3.1 summarises the requirements for the LIREC scenario adapted to our research goals.

Scenario Requirements	
Environment	shared room (workplace)
Robot Behaviour	mobile, speech capabilities
Interaction	Long-term
Subjects	Adults, n>1
Privacy	Shared between users

Table 3.1: Scenario Requirements

In a formal set-up like an office environment, social interactions with a robot can be quite distinct from traditional lab-based controlled experiments, as the users may not interact with the robot all the time given they need to carry out their routine work. The office environment offered an interesting avenue for our research, as it allows both the social and functional skills of the robot to be investigated and specifically the recharge behaviour. Very few long-term HRI studies have captured the overall experience from the users' perspective, sharing the same physical space with a mobile companion robot performing multiple tasks. Some previous long-term HRI studies have focused only on one aspect of the robot behaviour: for example, proxemics [122], hand overs, fetch and carry [104], passage behaviours [20] etc.

The LIREC project (finished in August 2012) designed a set of tasks for the robot in a workplace setting which provided some level of social interactions. Developing useful tasks for a robot is challenging given the technical limitations in terms of perception and understanding with currently available sensors. Other research groups that have studied human-robot interaction in workplace environments, the robots were deployed in neutral spaces like corridors [124] or reception [125] etc. where the robot is not always in close proximity with humans.

Having a robot in the same physical space as the human can pose privacy issues also it is more likely that the users become aware of the limitations of the robot as they can closely observe its autonomous performance over a long-term period. Also according to our literature survey, it appears that there have been no long-term studies on recharge behaviour of the robot in workplace environments where the users share the same physical space with the user. We envisaged that this work could provide us with novel understanding of the users perspective on the robot's recharge behaviour of a robot.

3.2.1 Scenario Requirement Specifications

The LIREC project had outlined the following scenario requirements which we adapted for our own research.

- **Key idea:** Robot acting as friendly helper for a work team.
- **Actors/Roles:** The scenario was tailored for adults. It involves interaction with one user at only a time but requires successful repeated interaction with a group of maximum six people and the ability to move completely in the shared office space.
- **Motivations for the user:**
  - Able to ask about people not present and important lab events
  - Personalisation of the interaction – the companion "remembers" what the user likes/dislikes and something about their personal life
  - Establishment of a relationship between the user and the companion
- **Activity Description:** The robot acts as a workplace buddy within a given lab inhabited by a small group of people. It keeps track of who is there, remembers for people who are not there where they have gone and why; knows about important collective events in the office like demos or equipment upgrades; important individual events like paper deadlines and project meetings, delivers messages left by other team members. The Team Buddy will interact with members of the group through a real robot, a Pioneer with suitable sensors including a camera.
- **Activity Model:** In the first interaction, the robot is introduced to each member of the team and acquires some basic information about them (age, sex). Thereafter it can be approached for interaction by a team member and can move around the office to initiate an interaction. It adjusts its physical position according to the interaction it is carrying out or according to its need to locate people or objects in the office. It has a "home" or default location to which it can retreat when not interacting. It must recognise a low power condition and either ask for help to recharge or be able to recharge itself.
- **Place/Setting:** The interaction takes place in a room with desks and lab equipment in fixed positions but some moveable items such as chairs, plus the occupants of the office as shown in Figure 3.1.

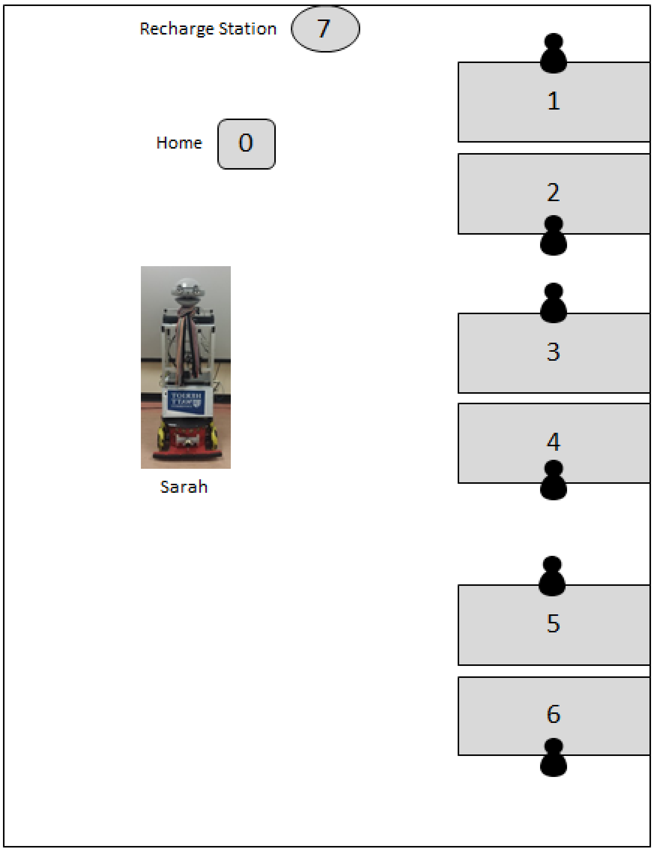


Figure 3.1: Map of the office environment, with desks marked 1-6 and 7: recharge station, 0: home/default position.

- **Behaviours/competences required:**
  - Ability to recognise a small set of individual people with some acceptable margin of error.
  - Ability to localise and navigate in the office without hitting fixed obstacles or impeding people moving around.
  - Ability to notice entries, breaks and exits in the room.
  - Ability to temporally localise in a human context: date; day (morning, afternoon)/night; working day/weekend/holiday; season-of-year semester.
  - Access and process internet information, for example: local weather forecasts, university news etc.
- **Artifacts/Media:** An embodied robot that can express its affective state and other social cues to the user through a graphical/robot face.
- **Time/Flow:** The scenario to be evaluated through a shorter-term basis (2 week pilot run) and a longer-term (3 weeks) study.

- **Research Questions include:**
  - Impact of recharge behaviour during long term HRI (our specific research goal was added to the overall project goals).
  - How to sustain engagement in longer-term interactions.
  - Acceptance/user experience - How users perceive the overall experience in the longer term in terms of enjoyment, levels of comfort in the interaction, social presence, etc.
  - Usability of the companion.

3.3 Robot Capabilities

Our research team performed a brainstorming session to select useful tasks for an office robot to perform. A brainstorming exercise has been used in some previous robot design methods to get feedback from users [126, 127]. The tasks for the robot were chosen based on technical feasibility as it can be very challenging to develop tasks which require a major hardware upgrade to the robot or logistical changes in the office. For example during the brainstorming some team members suggested tasks like bringing coffee, though the robot cannot prepare coffee, fetch and carry of printed material from the printer in the room, though there is no way to tell which user has printed in what order and the printer tray is located on the back of the printer near the wall which makes it harder for the robot to reach it. In particular when there was no gripper/manipulator installed on the robot.

Tasks: From the brainstorming the following tasks were selected and actually implemented for the robot (summarised in Table 3.2). The robot can greet participants when they arrived in office, deliver messages left by visitors/fellow workers, give reminders about events (from their Google calendars), carry a phone placed on its body to user's desk, pass remarks to the user by engaging in a limited social interaction by asking pre-programmed questions (these questions can change every day randomly).

The robot could sense the phone was ringing through a light sensor (the LCD screen on the phone is illuminated while ringing) and bring the phone to the nearest user present in the office. The robot could autonomously recharge its battery if the battery voltage went below a set threshold (battery low). The robot would wait at its home position when there was no active task and perform idle behaviours (making small idle motions with its head and eye blink). Providing idle motion for the robot also contributes to human perception while the robot is performing passive movements.

Nr.	Task Name	Task Description
1.	*navigateHome*	Navigate from interaction position (desk) to home (default) position after the task
2.	*dock*	Navigate and dock to the charging station when the battery is low
3.	*undock*	Undock from the charging station to home position when battery is charged
4.	remindOnMissedPhoneCall (NS)	Remind the user to check the phone for a missed call
5.	deliverMessage (NS)	Deliver a message left by a user/guest to a designated user in the office
6.	eventReminder (NS)	Remind the user of an upcoming event from their Google calendar
7.	logBookReminder (NS)	Remind the user to fill in daily diary
8.	greet (NS)	Greet the user when they first arrive in the office during a day
9.	makeRemark (NS)	Make small talk; e.g., "How is the weather today?"
10.	deliverPhone (NS)	Deliver phone (placed on the robot) when it starts to ring to the nearest user in the office
11.	ReplyWhereAbout	Tell the user where other users are (if they have specified so to the robot)

Table 3.2: Tasks for the TB. The tasks marked (NS) involves the robot navigating to a user's desk and speaking (TTS). The tasks numbered 1-3 are the system maintenance tasks and rest 4-11 are service tasks.

Previous work by Song et al. [128] describes the design of idle motions which service robots can perform in its standby state. They suggested that if a robot does not make any motion in their standby state, users may feel that the robot has been turned-off or even that it is broken. On the other hand, if robots do make idle motions, then this makes people feel that the robot is alive and are more they are likely to interact with it. The placement of the charging station and the home position in the room for our scenario was chosen from the feedback received from the brainstorming session and was located in a way that each user in the room could atleast partially see the robot in the room sitting at their desks.

Communication Interface: The tablet placed on the robot allowed users to login (and be greeted by name) and to tell the robot if they were going somewhere, and also to ask the whereabouts of other users if they have specified their status. The robot was equipped with text-to-speech capabilities using artificial an synthesised voice[2]. The robot had no speech recognition so users could only interact with it using a

[2]www.cereproc.com/

web-based android tablet interface placed on the robot. The robot would respond to request verbally, for example if it has seen the user on that day e.g., "I have seen X today" and would also speak out any status left by the other user e.g., "X is at a coffee break". The tablet interface could also be used to type messages for other users, to which the robot would respond "I got your message for X and will deliver it when I see X". Finally, the user could reply to small talk made by the robot such as "How is the weather today?" However, since the robot had no language understanding capabilities, it would reply to all queries by saying "ok". The robot would also carry out lip-syncing while speaking by moving the lower and middle discs on the EMYS head (explained later).

3.4 Research Methodology

In order to investigate both the goals of the LIREC project and the thesis research goals, we adopted an iterative and user-centric research methodology to gradually improve and validate our approach. The user centred approach is characterised by a strong focus on the user. The key idea is a series of iterative design cycles to evaluate and refine the interface. Many of the design principles in robotics have been inspired by the field of human-computer interaction Gould et. al [129]. The three proposed principles are: (1) early focus on users and task (2) empirical measurement (3) iterative design. The first principle focuses on understanding the user and task, through close contact with the user by means of interviews/feedback. These initial interviews/feedback should be constructed before the first design prototype. The second principle demands a careful investigation of how people interact with the device at hand. The third principle is to gradually improve the design through iterative development.

Investigating robot-human interaction from a user-centred perspective involves not only a consideration of the technological requirements of such a robot, but the study of psychological, social and cultural factors, which is a great challenge for HRI robotics research [16]. A user-centric study by Ljungblad et al. [130] surveyed participants that own exotic pets to investigate what kind of forms and roles of characters people are interested in. The idea of designing and validating scenarios rather than focusing on personalities for character design also proved to be useful for designing a personality for the personal robot PaPeRo [131]. Meerbeek et al. [132] described a process to design and evaluate personality and expressive behaviours and applied this to design the personality and expressive behaviour of a domestic robot. In our research we wanted to study the long-term effects of human-robot interaction in the office using the "Team buddy" scenario using an iterative user centric design approach. The user centric approach we adopted is described in Figure 3.2, with the flow of different studies/experiments that were performed in order to refine the scenario. From the top of the diagram each study/experiment fed into the next phase where improvements were made to the scenario. The segments in the diagram denoted by a circle show an iteration to the system. More details about these segments are described in sections in this chapter and chapters to follow.

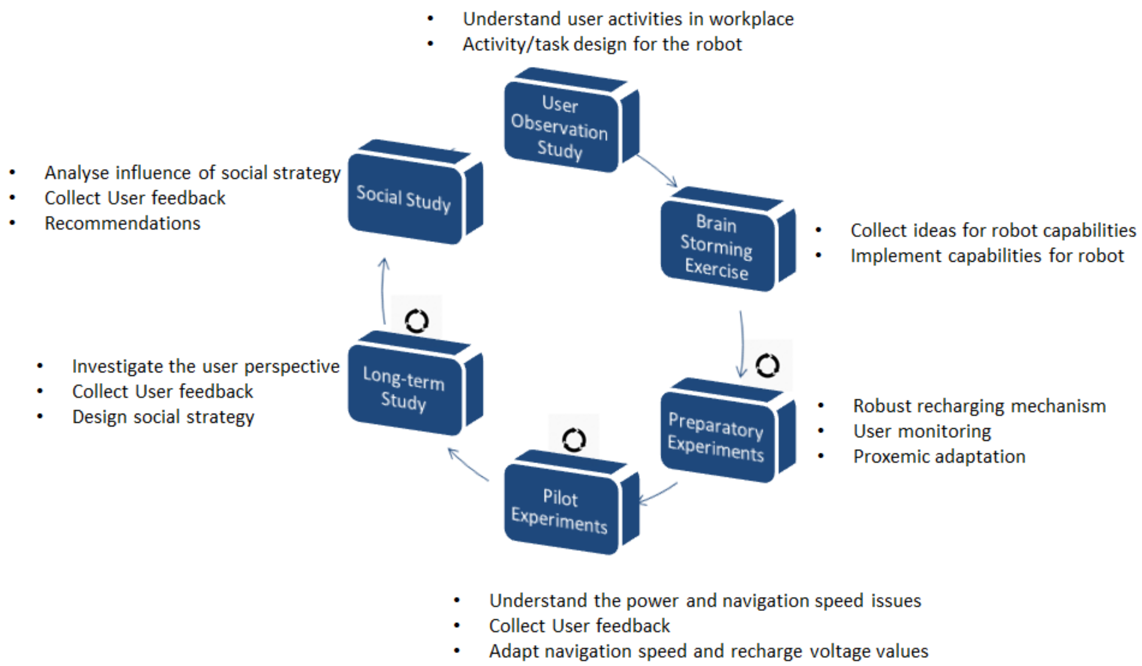


Figure 3.2: Research methodology flow, circles denote iterative development

1. **User observation study:** A User observation study was performed in order to understand user activities in the workplace which led to the initial design of various activities for the robot described in Section 3.4.1.

2. **Brainstorming exercise:** The initial design of activities were further used in the brainstorming exercise to define and develop concrete tasks taking into account the technical/hardware limitations of the robot. We also developed and modified the hardware for the robot (Section 3.5) which significantly improved the interaction capabilities of the robot for long-term operation.

3. **Preparatory experiments:** Preparatory experiments helped to test and improve the capabilities of the robot especially navigation, localisation and autonomous recharge capabilities for the robot described in Sections 3.6, 3.6.1, 3.7. From the user observation study, user monitoring capabilities for the robot were developed to perceive user presence information like Entry, Exit, Break (Section 3.8). Feedback from the participants in our proxemic study (Section 3.9.2) helped to validate our approach for the robot to obey social norms. The

distance of 0.51m was found to be comfortable while interacting with the robot approaching them.

4. **Pilot experiments:** Once the initial system was validated we performed pilot experiments to test the robustness of the system (covered in Chapter 4). User feedback was gathered and evaluated to make improvements to the system and to prepare it for the long-term experiment.

5. **Long-term experiment:** A long term study was performed with the aim of studying long-term interactions with the robot in a natural setting. The robot operated continuously in the office environment for three weeks, interacting with five participants (Chapter 5). The study combined quantitative questionnaires, interviews, the robot tasks and activity logging, along with a user diary to record their daily experiences with the robot. The long-term study helped to gain a deeper perspective on user attitudes toward the robot and perceptions of recharge behaviour of the robot.

6. **Social experiment:** The data and feedback received from the participants of the long-term study was used constructively to design a social strategy for the robot. A final quantitative study was performed with 50 participants by implementing social strategies for the robot to manage the user expectations in a socially acceptable manner (Chapter 6).

3.4.1 Understanding User Activities in Workplaces

In order to validate tasks and capabilities outlined for the LIREC project scenario, it was important to understand the primary activities that take place in an office/-workplace environment. An evaluative study carried out by Appel et al. on the effectiveness of activity-based office concepts [133]. Their research methods consisted of a wide research of relevant literature on workplace design, both from environmental psychological and economical perspective. They collected and analysed empirical data based on both an observation and a survey of 182 end users from four different service organisations in the Netherlands, using questionnaires. Appel et al. adapted taxonomy of activities of office workers from Tabak [5] and applied to typical office activities to produce a matrix of activities in Figure 3.3.

They suggested that activities can differ from each other in attributes like frequency, duration and importance also time of year can influence. From their results, in an average week, the respondents spent most of their working time in the office each day between 74-94% with an average of 86%. Due to meetings and physiological activities the workplaces in use were still empty at the time of the round for 38% of the times. The main activities were working behind the computer (34%), informal talk

	Social	physiological	job related	individual	group	planned	unplanned
behind the computer			X	X			X
writing			X	X			X
reading			X	X			X
on the phone			X		X	X	X
archiving			X	X			X
in a meeting			X		X	X	
informal talk	X		X		X		X
presenting			X		X	X	
lunch	X	X			X	X	X
toilet visit		X		X			X
coffee break	X	X					
other break	X	X			X		X

Figure 3.3: Activities of office workers, [5]

(12%) and being on the phone (6%). Appel et al. carried out their observation during summer as they suggested that advantage of using this period to do the observation rounds, is that people can express their actual preference.

User Activities Observation Study:

In order to understand the user activities of our office environment for a routine day, we conducted a two day observation study during September 2010. We selected Tuesday and Thursday as the mid-week days where most users were likely to present in the office (including part-time workers) and when none of them were away on holiday/conference. We manually observed and recorded the activities from the users mainly focusing on Entry (the first time users enter the office during that day), Break (User takes a break for more than 20 minutes from their desk), Working (when the users are working behind their computer), Discussion (when the users were discussing with each other), Exit (when the user exited the office at the end of the working day).

This study helped to identify the activity patterns in a routine working day in the office. For example what time they arrive in the office, take a break, leave the office etc (refer Figure 3.4). We anticipated that these primary activities (Entry, Exit, Break) will be important for the robot to sense and engage in an interaction with users. We chose only to observe the Entry, Exit and Break activities because for other set of activities presented by Tabak [5], it was not feasible for the observer to record the activities which were not occurring in the room itself (for example lunch, toilet breaks etc.).

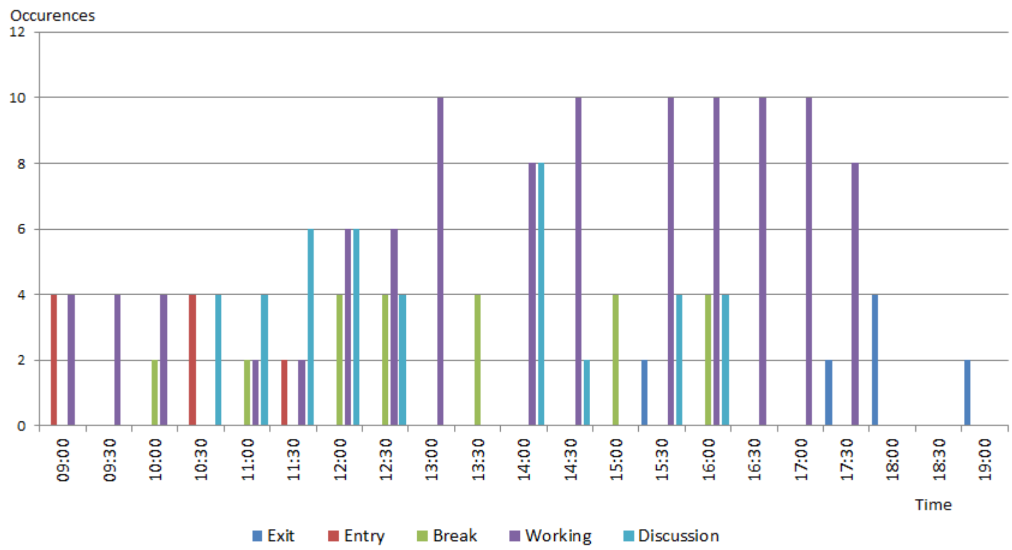


Figure 3.4: User activity patterns for users (Entry, Exit, Break, Discussion, Working)

3.4.2 Task/Activity Design

Based on the user activities observation study (Figure 3.4), we produced an outline activity schedule for our team buddy robot we named as "Sarah" with an example schedule (Figure 3.5) for a typical routine day for our robot.

Time	User	Robot
9am	Bruce enters the office and sits at his desk. Bruce replies Sarah – "I am fine, thank,you"	Sarah approaches him and greets him – "Hello Bruce, how are you today?" Sarah delivers any messages/reminder to Bruce for that day
11am	The phone starts to ring..	Sarah brings the phone to the nearest available user saying- "There is call for you"and waits patiently until the user has completed the call. Sarah then goes back to her home position
12pm	Bruce leaves a message for another user Amy	Sarah, receives the message and says - "I will deliver the message to Amy when i see her".
1pm	Users leave the office for lunch	Sarah recharges at docking station after users have gone during lunch break
2pm	Amy enters the office and sits at her desk	Sarah greets Amy and delivers the message left by Bruce - "There is message left by Bruce, reads out the message"
4pm	Amy has an upcoming meeting	Sarah approaches Amy and reminds Amy of the meeting - "Amy you have a meeting shortly"
6pm	Bruce finishes his working day and leaves the office	-
7pm	Amy finishes her working day and leaves the office	Sarah recharges at docking station after users have left after work

Figure 3.5: Example activity routine for "Sarah"

3.5 Robot Design

At the start of the LIREC project, Heriot-Watt research team had a Pioneer P3AT robot [44]. Systematic modifications were made to the robot in order to make it suitable for the office workplace buddy scenario. Although the physical design of the robot was not the main goal of our research it was important to develop a robot platform suitable for long-term human-robot interaction and to meet the scenario requirements mentioned in Section 3.2.1. In this section we describe the design developments/changes made to the robot in order to carry out our research. The hardware development was performed with the help of a technician from electrical engineering department following our guidance.

3.5.1 Robot Height

The initial version of the robot was very short in height (30 cms) and thus not well suited for face-to-face human-robot interaction for our scenario, Figure 3.6 (left). We upgraded the physical structure of the robot by developing a superstructure to increase the height of the robot. Previous research has indicated that robot height plays an important role in people's perceptions of a robot and their interactions with it, so is also found to be true with human-human communication [134]. For example, Walters [135] found that participants judged shorter human-like robots to be less conscientious than taller human-like robots. In a robot design study by Lee et al. [136], users preferred the taller robot version of 56 inches (142 cm) to shorter versions because they did not want to bend down to interact with it. A Robotic telepresence systems study by Rae et al. [137], showed that, when the robotic system was shorter than the user and the operator was in a leadership role, the user found the operator to be less persuasive. Furthermore, having a leadership role significantly affected the user's feelings of dominance with regard to being in control of the conversation.

We anticipated that most of the interactions in our scenario will take place while the user is sitting at their desk and the "Team Buddy" was like a peer to the workers in the office. We envisaged the robot should be of a similar height as the user (in a sitting position) and shorter when the user is standing and interacting with the robot, so that there is less influence of dominance or perceived power relationship of the robot with the user. Hence, we constructed a superstructure on the robot which would increase the height of the robot to 1.20 meters (47 inches), roughly at a user's eye level while sitting on a chair at their desk. We measured the approximate eye level height of 5 users which depends on their personal height and how they adjusted the height of the their chair, which was found to be roughly between 40-50 inches high. The upgraded robot height (1.20 meters, Figure 3.6 right) also conforms with previous studies in human-robot interaction about height of the robot [137], [136].

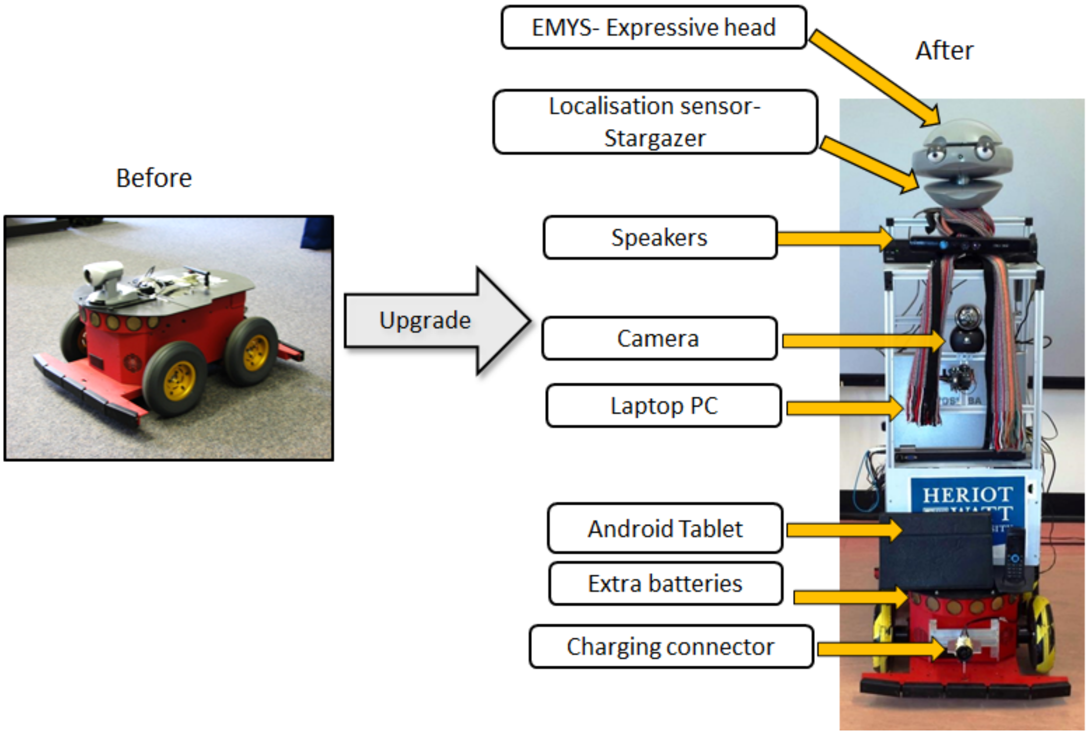


Figure 3.6: Left: Robot before upgrade, Right: Robot after upgrade-“Team Buddy” (TB) with enhanced superstructure, height 1.2m

3.5.2 Robot Hardware

As the robot initially had limited sensors[3], 4 motors/wheels with encoders, microcontroller, Front and rear SONAR arrays (8 on each side) for obstacle avoidance. We equipped it with additional sensors. This included a camera placed in front of the robot on its torso. A Stargazer sensor for indoor localisation [138] (explained in detail in Section 3.6.1) was also added. For computation a laptop PC[4] (Toshiba T6570, Intel Core 2 Duo processor, battery: Lithium-ion 56Wh), was installed on the robot. An expressive head EMYS [139] developed by LIREC project partners was installed on the robot in order to express robot's internal emotional state (Happy, Sad, Neutral). Given the fact that additional hardware increases the power requirements of the robot, the robot's battery capacity was doubled from 3 to 6 lead acid batteries (6 $\times$ 12V, 7Ah = 504 watt hours) offering an approximate operational time of 3 hours when fully charged (depending on usage). These require about 3 hours to recharge. The robot was also equipped with Phidgets sensor[5] relays boards (controls the switching of sensors, actuators, laptop) and power measurement sensors to measure power consumption on sensors, actuators and the laptop. Figure 3.6 shows the robot before upgrade (left) and upgraded robot (right).

[3] http://www.mobilerobots.com/Libraries/Downloads/Pioneer3AT-P3AT-RevA.sflb.ashx
[4] http://www.toshiba.co.uk/discontinued-products/tecra-m10-1k1/
[5] http://www.phidgets.com

3.6 Navigation

In order to interact with the users and perform tasks, the robot needs to move close to users' desks and navigate in the room without hitting obstacles. There have a been a variety of approaches for autonomous robot navigation. We employed a local navigation method that relies on current and local information from sensors to give the mobile robot an online navigation capability which can be computationally efficient compared to grid based approaches [140, 141]. We focused our approach on simplicity and efficiency, we employed a local navigation technique based on potential field method for navigation which been used extensively for mobile robot path planning [142, 143]. The potential field method does not require a previously known map of the environment to be provided to the robot. In the traditional artificial potential field methods, an obstacle is considered as a point of highest potential, and a goal as a point of lowest potential. Although many forms of potentials have been studied, the concept behind them is relatively simple. The basic concept is to fill a map of the workspace with an artificial potential field in which the goal exerts an attractive force (-) on the robot and every obstacle exerts a repulsive force (+). The vector sum of all forces give the resultant direction and speed of the robot's motion at any given position, refer Figure 3.7, [140].

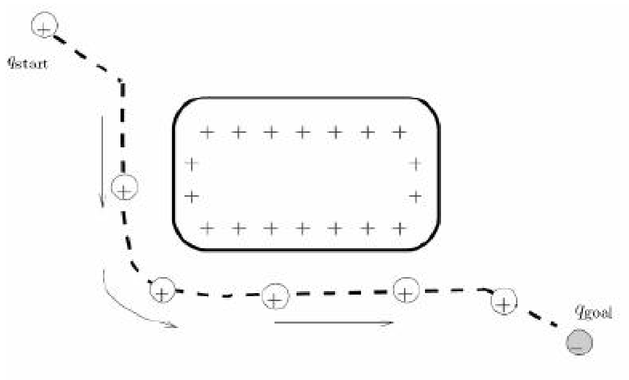


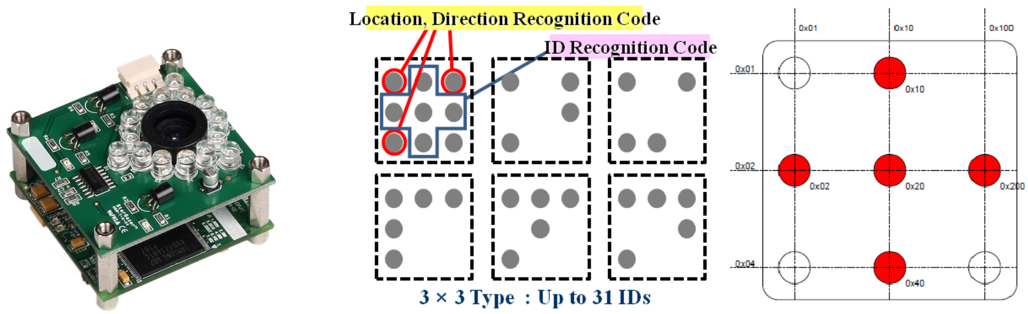
Figure 3.7: Potential field and gradient forces acting on the robot to achieve complete path [140].

The potential field method for path planning has some limitations, namely; local minima; oscillations in the presence of obstacles; absence of passage between closely spaced obstacles; and oscillations in narrow passages. We envisaged a mechanism where the robot can ask for help verbally to clear away obstacles to the users in the office in the case where it gets stuck in a local minima. The approach of asking for help to overcome hardware and potential algorithmic limitations by the robot was explored by Rosenthal and Veloso [144]. In this work, they focused on mobile robots that can proactively seek humans in offices assist with travel to the target location (e.g., to push buttons in an elevator or to make coffee in the kitchen).

3.6.1 Localisation

Along with the navigation capability it was important to develop a robust localisation capability for our robot. Localisation using methods like dead-reckoning (odometry) consists of periodically measuring the precise rotation of each robot drive wheel (using for example optical shaft encoders). The robot can then calculate its expected position in the environment, if it knows its starting point of motion. The main problem with this technique is drive wheel slippage. If this occurs at the drive wheel, the encoder on that wheel would register a wheel rotation, even though that wheel is not driving the robot relative to the ground. The other problem is that the errors accumulate thereby causing the robot to have incorrect information about its environment. The problem with wheel slippage was evident during our initial tests with navigation. With the major hardware upgrade to our robot reported in section 3.5 (Figure 3.6), increasing the weight of the robot, the wheels had to be taped in order to reduce the friction between the wheels and the carpeted floor in the office.

To reduce uncertainty during robot localisation, we installed a localisation sensor on the robot called StarGazer™ from Hagisonic co. ltd.[6], sensor system used for indoor localisation of intelligent mobile robots (Figure 3.8a). The sensor analyses an infra-red ray image which is reflected from a passive landmark placed on the ceiling with an unique ID for each landmark. Through an on-board digital image processing unit, the sensor calculates the position and angle of a robot by analysing the acquired image (Figure 3.8b). The output data provided by the sensor includes the position (X, Y) and heading angle of a robot in relation to the landmark identified. The sensor is robust against noise such as infrared light, fluorescent light, sunshine and it works well at night (dark) in low light conditions as well. The power requirement of this sensor is low (12 V: 70 mA), can read landmarks at 20 times/sec, with a precision of (+/-) 2 cm and an angle resolution of 1.0 degree.



(a) StarGazer™ Sensor (b) Passive Landmark ID

Figure 3.8: Stargazer and Landmarks

[6]http://www.robotshop.com/media/files/pdf/stargazer_user_manual_ver_04_080417(english).pdf

The landmarks do not require power source as they are passive, so the system is easy to set-up. Each landmark can cover an area of 2 square meters. 20 landmarks were placed at intervals of 1.5 m on the ceiling so that there is no dead zone in the room where the sensor fixed to the robot cannot see a landmark, refer Figure 3.9. Using the potential field method discussed in Section 3.6, we developed an algorithm to calculate the angle and direction required (in relation the sensor reading provided by the stargazer sensor) in order for the robot to navigate to a goal position in the room. We envisaged that the robot in our environment does not require an accuracy of more than 0.5 sq meters as during most interactions with users in the office the robot just needs to come close to user's desk.

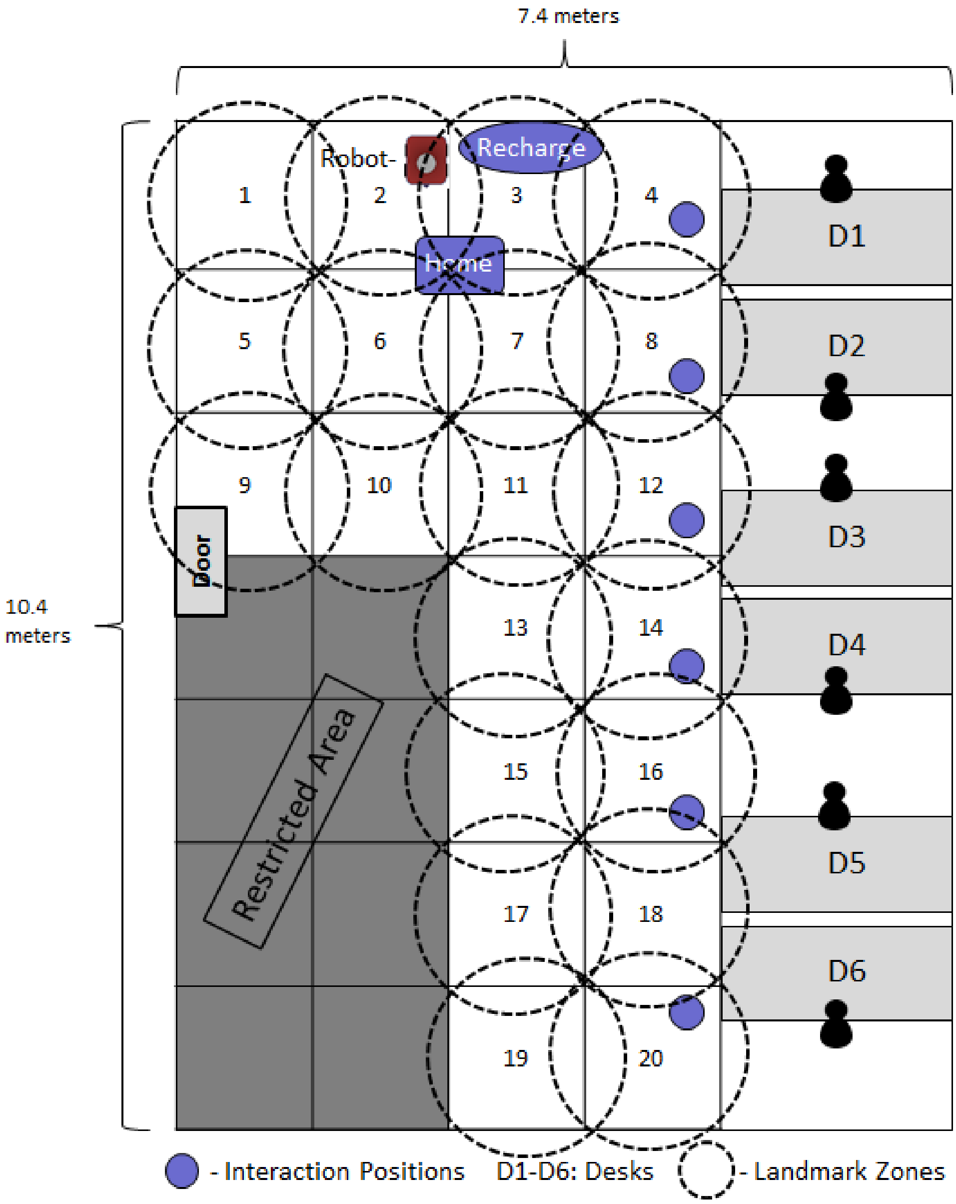


Figure 3.9: Landmark Setup map, landmarks ID's: 1-20, (Map not to scale)

Summary: An important task in meeting our research goals both of the LIREC project and this thesis was to develop a reliable and robust navigation for our robot. Other approaches using probabilistic navigation is required primarily because of the poor information content of range-finding sensors [145, 146]. We anticipated that navigation using potential field method and localisation using stargazer sensor might obviate the dependence on probabilistic approaches like SLAM [147], thereby introducing significant computational and power savings to the robot which was necessary for our scenario.

3.7 Autonomous Recharging

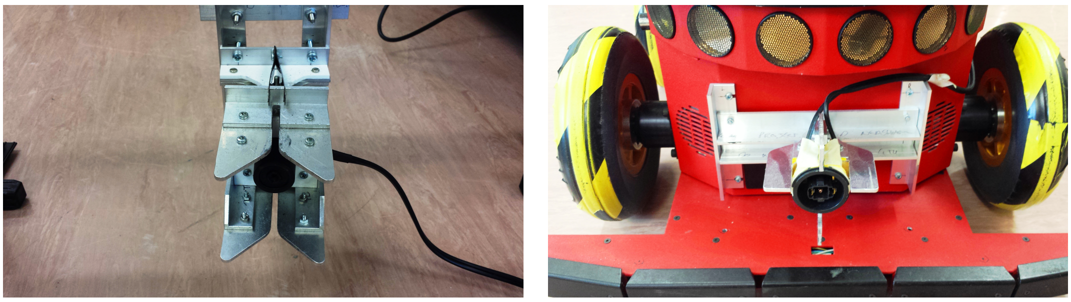
Along with a robust navigation capability it was important to develop a recharging mechanism for our robot. The recharging capability was very important to our work as the robot was required to operate over a long-term period without any human assistance. We presented some approaches to autonomous recharging in the previous Chapter 2 Section (2.2.2). The auto recharging process commonly involves 3 main steps; 1) finding the charger, 2) approaching the charging station and 3) plugging into the charger (in the case of wireless charging, coming close to the charger). Most of the existing approaches involve navigating to the charger using visual markers used as beacons. The robot platform we used, the Pioneer P3AT from Adept mobilerobotics, provides a recharging station which requires additional complex electronics to be installed internally, at a high cost[7]. Also the robot cannot be fully recharged due to system limitations (i.e. computer and other systems modules running during recharge). Operational time is therefore limited before another recharge is necessary. We therefore decided to build our own charging system.

Other research groups working with Pioneer robots have also built custom charging stations designed for Pioneer 2DX robots, as described in [70]. In this work, the robot after an unsuccessful attempt at docking, moves away from the docking station a short distance and repeats the docking procedure. Other than Pioneer-based recharging systems, work by Hada at al. [148, 64], describes a recharging system with increased functionality and repetitive docking over the course of a week using a robot similar to the Pioneer robot. Sensors are an important part of their docking strategy, providing them with the information needed to find a large docking station that houses the robot during the recharge process. This previous work influenced the design of our recharging mechanism.

[7] http://www.mobilerobots.com/Accessories/ChargingSolutions.aspx

3.7.1 Recharge Mechanism

A plug-in faster charger is supplied with the Pioneer robot from Adept mobilerobotics, manufactured by Power Sonics Corp, which provides a 12V, 4A power supply. We integrated this plug-in charger into our docking station to keep the electrical design simple and cost effective. We designed and fabricated the charging connectors locally in the University. These consisted of two main parts, the charging connector fitted on the charging station and a connector on the robot, refer Figure 3.10. The connector on the charging station was connected to the plug-in charger (Figure 3.10a) and the connector on the robot's front side was connected to the robot's on-board batteries (Figure 3.10b). We used a kettle connector for the actual charging end points as these pass the safety standards and leave no electric ends exposed. Both the connectors were designed to be compliant, to allow approximately 25 deg. error on the horizontal axis. This would allow the robot to approach the charging station at an acceptable angle (+/- 25 degree) and still manage to make a connection with the charging connector even if it's not perfectly aligned to the centre of the connector. Our recharge connector design provided a less complex and cheaper solution compared to other designs [2, 3] with a error-compensation capability. Designs of the connectors are described in Appendix A Section A. 1.

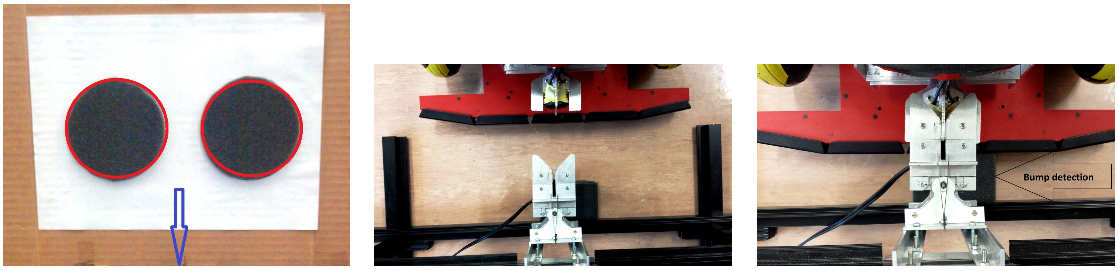


(a) Charging Connector (b) Robot connector

Figure 3.10: Recharging connectors

Informed by literature covered in Chapter 2, Section 2.2.2. The most commonly used and reliable auto-recharging approaches are based on visual servoing. Also utilising the limited sensors we had on the robot (camera, sonar, stargazer), we developed an auto-recharge mechanism based on a visual servoing approach. A visual marker is used by the vision system on the robot to guide the robot into the charging station. The visual markers were placed on the recharging station, and consisted of two black coloured circles (diameter 10 cms each) separated by a distance of 4 cms. The vision system uses the camera placed on the robot to find two circles in an image using the Hough transform using OpenCV library (open source computer Vision library) [149]. Once the robot is guided by the navigation module to the start position (facing towards the charging station), the docking process then begins. The vision system calculates the mid-point between the two circles (indicated by the arrow, Figure 3.11a), which are in vertical alignment with the charging connector and aligns the robot's position to the the centre point of the two circles (circled red in the Figure 3.11a)) via the robot's navigation system.

The robot can then approach the charging station in a straight line slowly until the bump sensors on the robot make contact with the base of the charging station. The charging connectors then make contact with each other; the bump sensors, when triggered, stop the robot from going any further (obstacle avoidance behaviour is performed using only the bump sensors while docking). The power monitoring system then senses the changes in the voltage, taking a reading from the robot's batteries every 10 seconds. If the voltage has increased after 3 iterations (30 seconds) then it is sensed as a successful dock.



(a) Visual markers (2 circles)

(b) Robot approach towards charger

(c) Docking sensed with bump detection

Figure 3.11: Docking steps

We performed a controlled experiment to determine the approach angle and the position for the robot in order to achieve a successful dock. We explored various angles and positions where the robot faced towards the charging station and docking was initiated. The angles were -60°, 90° and 60° which allowed the vision system to have the visual markers (2 circles) in the field of view of the camera. We used 35 different positions for the robot in a 3.5×3 meters area, the area was divided into 0.5 sq. meters for each cell using 3 different angles (-60, 90, 60), in total $35 \times 3 = 105$ total combinations. The area beyond the 3.5×3 meters was not considered as we observed that the vision system could not detect the visual markers. The charging station was placed in the centre of this exploration area.

Figure 3.12 shows the results. The cells coloured red where docking failed due to an incorrect approach angle when the charging connectors could not establish an electronic bond for the charging to take place. The cells coloured orange are positions where the docking only succeeds if the robot is at an angle of +/- 60° depending if the robot is to the right/left of the markers. The area shown in green is where the docking is successful 91% of the times. For the robot to have a high chance of a successful dock the robot should ideally start the docking process from the green zone, ideally from the 1.5 meters mark; this cell is marked with a dashed border. Furthermore, we also incorporated a recovery mechanism where the robot retracts from the charging station after an unsuccessful dock and reattempts the docking from the start position. An unsuccessful dock is determined if the voltage does not increase in the 30 seconds after the bump sensors are triggered. This may be due to the charging connectors not making a good connection for charging to initiate (recovery mechanisms were not used for this particular experiment). Other docking approaches [2, 65, 66, 68, 3, 69] did not report they handled the issues with docking failures.

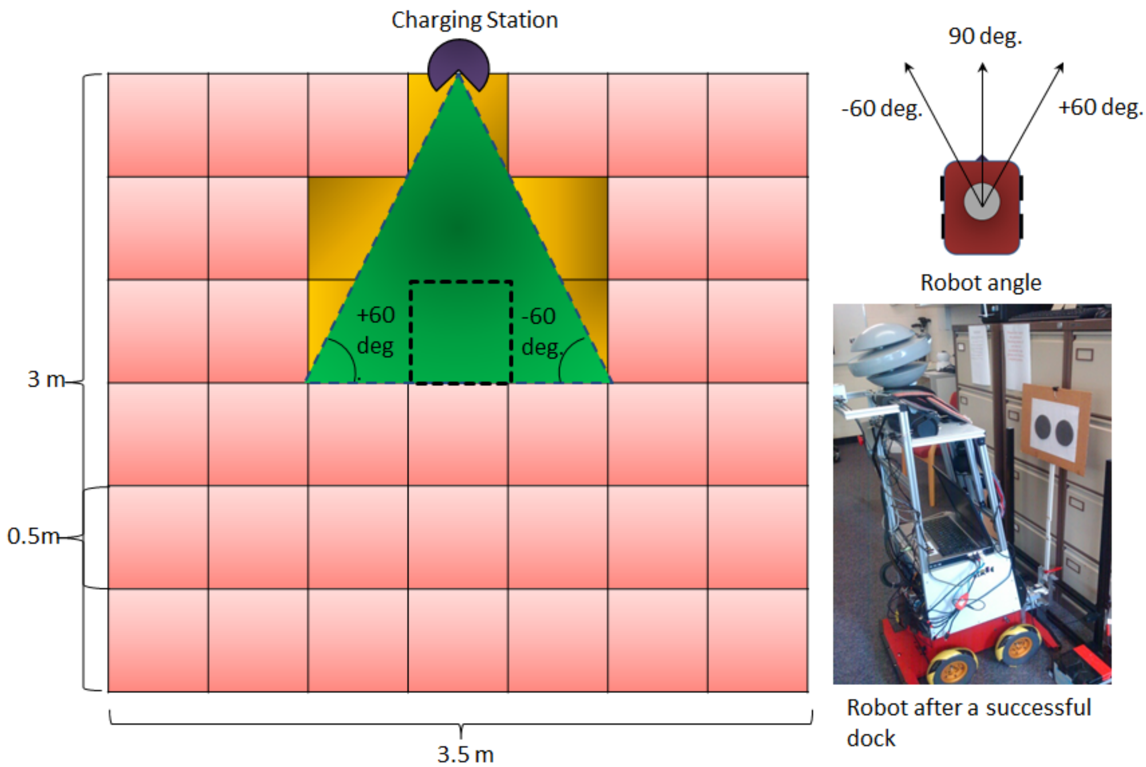


Figure 3.12: Robot docking experiment

We designed the auto-recharge mechanism so that the robot in its low power state could navigate to any point in the green zone facing the docking station and approach the marker slowly. The vision system can then guide the robot to the docking station and connect to the charger installed at its base platform (Figure 3.12). Images were captured by the camera at 15 fps with a resolution of 640 $\times$ 480 pixels. The computational usage for this docking algorithm was on average 5%. The actual docking time was on average 100 seconds and speed while docking was set to 50 mm/sec. The speed during docking was set to a lower value in order to allow the robot to adjust its position and angle of rotation in relation to the charging station in a timely manner. Obstacle avoidance using the robot's sonar was disabled so that the robot can get close to the charging station and bump sensors were used for obstacle avoidance while the docking was active[8].

3.8 User Monitoring

In a workplace environment it is quite challenging to keep track of a specific user's location and perceive whether they are present in the room. The most reliable techniques used for tracking specific users in real time involve users wearing active RFID tags which was not desired by the participants and to make sure it's charged/used all the time [150, 151]. As discussed in Section 3.4.1, in order to engage in an interaction, the robot must have perception abilities such as detecting whether a user has entered the room or is sitting at their desk. From our two day observation study, we developed a mechanism for the robot to detect users presence status, primarily (Entry, Exit, Break).

In our scenario, a group of maximum 6 users can work on their assigned desks, each of which has a desktop PC (users work stations), we attached a web camera over their PC screen facing in the direction of the user. We developed a program that runs on their PC, the program is able to detect if a particular user is present/absent at their desk. The program uses a standard face detection algorithm with OpenCV [152] to detect a face in front of the web camera. Additionally, the program can monitor users' keyboard and mouse activities. The user's presence information (averaged every 5 second intervals) is then communicated to a central server in the room which then sends the user's presence status to the robot.

The program utilises only about 2% of the CPU resources on each user machine, so it does not impact the user's work-flow. Moreover, it allows the system to collect user presence information without requiring the users to wear active tags. Using face detection along with keyboard and mouse input gives a better prediction of users' presence or absence at their desk. For situations when the user is reading, which may not involve keyboard or mouse activity, information from the face detection process is useful.

This approach is not 100% accurate in determining the user's presence at their desk, for example when the user is not using their PC and not facing the PC screen. However, our approach helps to acquire presence information; this is very challenging to achieve using other techniques. The robot could also identify users at their desk using this approach as each user had a dedicated desktop work PC to which the camera was attached. We used time-outs to perceive events such as break, entry and exit. The time-outs are basically events triggered when a particular user is not detected for specified time intervals. For example, Break: 20 minutes, Exit: 600 minutes, Entry:

[8]Video of autonomous docking test can be seen at: `http://www.macs.hw.ac.uk/~amol/download/phd/DockingTrial.mp4`

User detected after 600 minutes.

3.9 User Proxemics adaptation

Earlier studies have shown that successful human-robot interaction is impacted by adopting comfortable approach distances between human and robot that respect the user's personal space [153]. Studies also indicate that the appearance of the robot influences the level of comfort in relation to approach distances [154]. Peters, et al. [155] developed an approach based on spatial prompting by a robot and a human for appropriate passing behaviour in a narrow hallway, where human and the robot have to make room for each other. Some researchers have assigned more precise numerical values to personal spaces in human to human interaction, Hall [120]. Hüttenrauch et al. [156] concluded from their study that most participants kept inter-personal distances from a PeopleBot^{TM} robot corresponding to Hall's personal spaces (0.45m to 1.2m). A study by Walters et al. [153], suggest the mean comfortable approach distances vary from 0.65m to 0.5m depending on the appearance of the robot e.g. humanoid, mechanoid [154].

We anticipated that people will assume distances that correspond to social or personal zones (similar to distances people use having face-to-face conversation) while treating a robot as a *social being*. In our scenario the "Team Buddy" interacts with members of the group through a Pioneer^{TM} robot with enhanced superstructure (mechanoid appearance). In order to act as a workplace buddy to a small group of people, it is necessary for the robot to be able to approach users so that it can initiate interaction with them and maintain a comfortable distance from them. We developed a mechanism that makes use of face detection for sensing user proximity taking into account user proxemics studies.

3.9.1 Face Distance Calculation

We used OpenCV [152] for detecting faces in the environment, as discussed earlier (Section 3.8). We used face detection to further estimate the position and distance of human face in relation to the camera placed on the robot (using the bounding box of a human face). We performed a small experiment using 5 participants facing towards the camera positioned at specific distances in a straight line, and recorded the difference between the image area and face bounding box detected by the face detection algorithm.

Intuitively, the closer the face from the camera, the larger the face bounding box area will be and vice-versa. We used a camera with a resolution of 640×480 giving us a constant image area of 307200 (pixels). As the total image area is always constant, it was straight forward to record the difference between image area and face bounding box area in pixels. Since the robot lacked sensors which would give us reliable distance from the human, we used this approach to approximate the distance between the robot and human.

$$\textit{Equation 1: } AreaDifference = ImageArea - FaceBoundingBox$$

We performed an experiment with 5 subjects (4 Male, 1 Female). Each was positioned at a specified distance (0.3m, 0.5m, 1.0m, 1.5m, 2.0m and 2.5m) from the camera and we recorded the image area difference (AreaDifference). Each reading was averaged over 20 samples taken at each position. The graph in Figure 3.13 illustrates the area difference readings (Y-axis, pixels) for each distance position (X-axis, meters) for 5 subjects P1 to P5 and the average area difference for the 5 subjects. We can observe from the points in the graph that the area difference values are quite similar for all 5 subjects (P1-P5) for all 6 distance positions and the pixel area difference increases as the distance of the detected face from the camera increases.

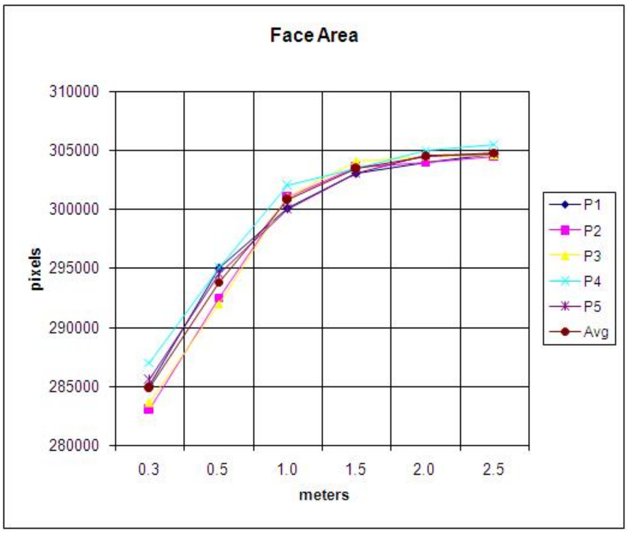


Figure 3.13: Face area graph

We thereby established that image area difference can be used effectively for user distance approximation using a face area bounding box. Please note that the pixel values may vary with different camera resolutions, but we anticipate that the ratio between AreaDifference and FaceBoundingBox pixels will be similar. We performed the experiments in well illuminated light conditions and recorded the average over 20 samples to test and improve the accuracy of the face detections.

We also performed physical observations while recording the samples, to confirm if a face was present when we recorded the sample. Out of 20 × 6 (distance positions) × 5 (subjects) = 600 (total recordings), Total false detections = 56 (no face was present, but detected, 9.3%), No Detections = 41 (face was present, but not detected, 6.8%), overall face detection accuracy was 83.8%. The results from the studies made earlier [120] and our average face area difference values are combined in Table 3.3.

Face Distance	**Spaces [120]**	**Area Difference (Equation 1)**
3m - 2m	Social Zone	304410
2m - 1m	Social Zone	303400
1m - 0.5m	Personal Zone	294000
0.5m - 0.2m	Intimate Zone	284620

Table 3.3: Face distance calculation and personal spaces

3.9.2 Face Position Estimation

To further estimate the position of the detected face to the left or right from the camera's focal point, our algorithm calculated the difference in number of pixels from the face mid-point to center X-axis in the image. This pixel difference can be further used by the vision module turn the robot (left/right) towards the detected face while approaching the user (see Figure 3.14a). This position adjustment approach is similar to the docking mechanism mentioned earlier in Section 3.7.1.

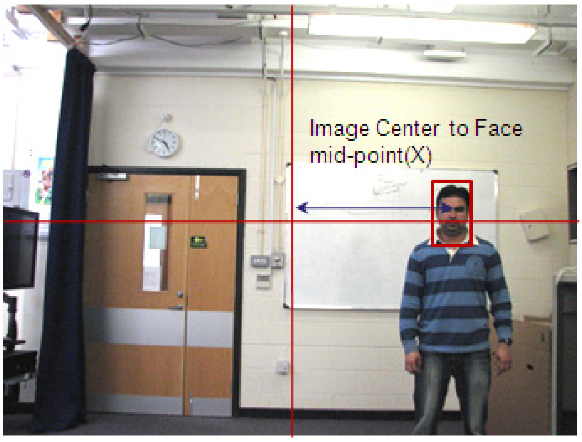
3.9.3 Automatic distance adjustment

To enhance our approach we developed a mechanism for the robot to autonomously adjust the distance from the user. The robot can move backwards (0.3m - 0.5m, 284620 - 294000 area difference in pixels) which corresponds to the human intimate zone (Table 3.3) if it gets too close or the user chooses to approach it. When the robot detects a person stepping back, it can approach them to maintain its threshold (0.5m, 294000 Area Difference in pixels) which corresponds to the personal zone (Table 3.3).

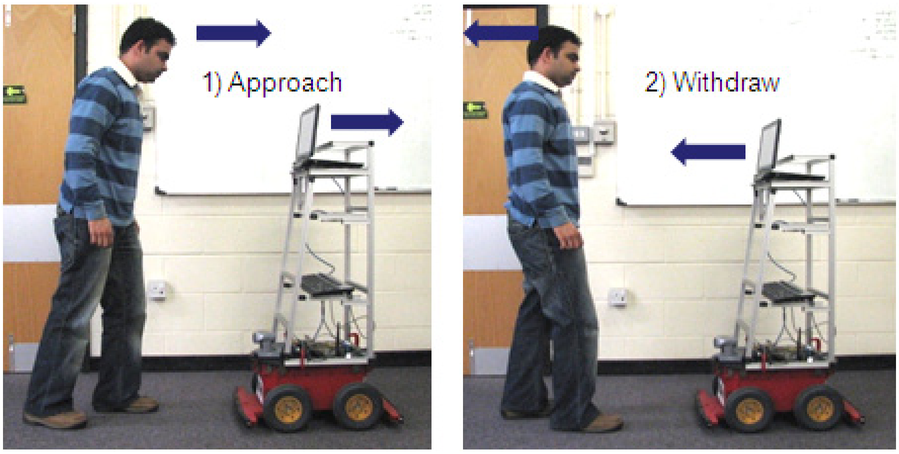
This mechanism provides an added advantage to user proxemic distance control while the subject is moving. Figure 3.14b illustrates the automatic distance adjustment. The face distance estimation algorithm was used to autonomously guide the robot towards the user and stop at a desired distance of 0.5m (Personal zone) from the user. When multiple users are present in the environment, the robot can approach the closest person facing the robot.

Experiment

We conducted a preliminary experiment to test the effectiveness of our algorithm and to find out how people felt about the robot approaching them. The trials were carried



(a) Face position estimation



(b) Automatic distance adaptation

Figure 3.14: Autonomous Proxemics

out independently with 5 human subjects (4 male, 1 female). We conducted 3 trials per subject (total 15 trials), placed at 3 different positions in the room facing the robot within range of 2 meters. At the end of 3 trials, each subject was given a short questionnaire and was asked to rate the robot between 1 to 5 (5 being the best) for each of their answers.

1. Did you think the robot detected you and was actually approaching you?
   Average score 4.4 after 15 trials.

2. Did you feel comfortable when the robot approached you?
   (a) It was acceptable: 5 Participants, average score 3.95 (b) It was discomforting: None (c) can't say: None

3. Did you feel comfortable when the robot moved backwards when you tried to approach it?
   (a) It was acceptable: 4 Participants, average score 3.6 (b) It was discomforting: 1 Participant, score 3.7 (c) can't say: None

The feedback from the questionnaire and average stopping distance measured after 15 trials (0.51m) indicate that people found the robot's approach acceptable (average acceptance score: **3.95**) and is in good agreement with previous studies on robot to human approach distances [153, 154, 120, 156]. Although when the robot moved backwards, 4 participants were comfortable with it (average score 3.6) but one participant found it uncomfortable (score 3.7).

Using this automatic distance adjustment approach along with the navigation algorithm mentioned earlier (Section 3.6), the robot can conform to social norms by maintaining its physical distance from users while interacting with them [122]. It should be noted that this study was performed with a static graphical human face "Greta" [157] displayed on the laptop placed on the robot (Figure 3.14) as the robot head EMYS was not yet installed during this experiment.

3.10 System Architecture

In this section we describe the LIREC architecture used in our scenario. Architecture innovation was not the focus of the research in this thesis, so we used the LIREC project architecture to carry out our research, shown below in Figure 3.15, and followed by description of each component.

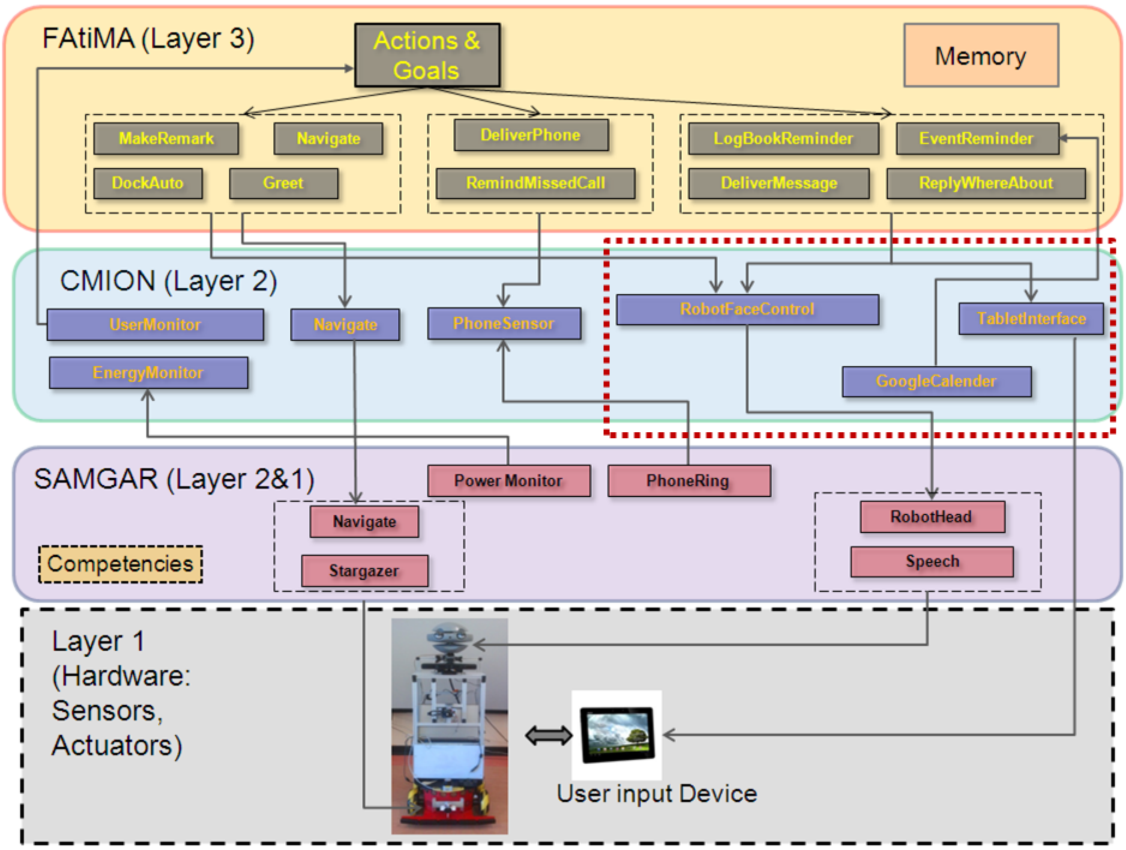


Figure 3.15: System Architecture

- **Layer 3:** Maintains high-level memory; carries out cognitive appraisal; manages goals; generates plans (action sequences); monitors plan outcomes. Layer 3 also defines a mechanism for organising activation and deactivation of competencies, and routing their inputs and outputs to Layer 1 through Layer 2. FAtiMA (FearNot Affective Mind Architecture) [158] is an extension of BDI (Beliefs, Desires, Intentions) deliberative architecture [159] that contains a reactive component mainly responsible for emotional expressiveness and it also employs the OCC [160] emotional influences on decision-making processes. The actions defined in Layer 3 are the tasks for the robot.

- **Layer 2:** CMION [161] is responsible for selecting concrete competencies to perform symbolic commands selected by Layer 3 and providing symbolic perception inputs to the Layer 3. Competencies are modules that abstract physical sensors and actuators to logical ones; run sensor and actuator-related programs; maintain low-level memory; pass information to layer 3 and accept goal directed constraints on competencies from layer 3.

- **Layer 2 & 1**: SAMGAR links Layer 2 and Layer 1, SAMGAR [162] utilises the YARP [163] framework that supports distributed computation and communication between modules and provides an easy way to connect modules in the system.

- **Layer 1:** Contains the physical sensors, actuators and user input device (Android tablet).

FAtiMA was developed in another EU project [164], CMION [161] and SAMGAR [162] were developed as a part of the LIREC project's generic architecture. The definitions for goals/actions for FAtiMA and implementations of competencies for CMION and SAMGAR were developed in this thesis work. Only the specific modules CMION (shown in dashed box in Layer 2- Figure 3.15), RobotFaceControl, TabletInterface and GoogleCalender were developed by project team members, all the rest of the modules shown in the architecture diagram Figure 3.15 were developed as a part of this thesis.

The design decisions for the scenario and capabilities for the robot were taken collectively as part of the project, however the actual implementation of the capabilities was developed in this thesis. The architecture in our scenario was reactive, meaning that the robot performed tasks when the pre-conditions were satisfied; for instance, carrying the phone to the nearest user present in the office when it started to ring (sensed by a light sensor on the phone). The robot could not execute tasks in parallel (this was a limitation of the FAtiMA component). For example, if it had to greet two people at the same time, it would greet only one user, return to its default position, and then greet the next one. Appendix Section A. 2 provides full description of modules used on the robot.

3.11 Summary

In this chapter we described our approach to the scenario design, tasks, robot modifications and capabilities developed for the robot to carry out our research. We used design considerations from the background chapter to develop an approach for an auto-recharge mechanism for our robot. The developed technical capabilities helped to define concrete tasks for the robot (summarised in table 3.2) which the robot could perform during long-term interaction. An overall system architecture was described in Section 3.10 with components used in the system. We then described our research methodology based on a user-centric approach which would allow us to make iterative improvements to the system (Section 3.4). In the next chapter we describe some pilot experiments performed to test and improve the system in order to prepare it for the long-term study.

Chapter 4

Pilot Experiments

In this chapter we describe two pilot experiments carried out to understand the technical challenges for running the scenario specified in the previous Chapter 3 for long-term operation. The pilot experiments provided technical and social insights to adapt the approach to better suit long-term operation in the final scenario. In Section 4.1 we describe navigation trials conducted and Section 4.2 presents our pilot long-term study.

4.1 Navigation Experiment

In order to understand the power requirements and to test the robustness of the navigation capability of the Team buddy robot (TB), repetitive navigation runs were performed. These runs involved the TB navigating autonomously from its default location (home position) in the office to a desk and performing a verbal action, similar to its actions during the final scenario. A Phidgets[1] sensor, was used to log the power consumption on the laptop, mobile base (motors, sonar), CPU Usage and distance covered during navigation. Figure 4.1 shows the lab map with user desks (1-6) on the right side, the home position and the recharge position (7) in the room.

During the experiment, we programmed the robot to autonomously navigate to different positions (1-7) in the room randomly and then return to the default position (0) on each occasion. The robot operated for several hours until a point where the battery voltage became low due to which the robot stopped working. We measured the battery voltage at this point to observe at what voltage the robot becomes non-operational. The robot continued to operate after a recharge (the robot was manually recharged during this experiment) and we also recorded the time and voltage required for the robot to fully recharge (until the led light on the charger became green after a full battery recharge). This experiment was carried out over 2 days including the

[1] http://www.phidgets.com/products.php?category=0&product_id=1018_2

breaks during recharging and the robot navigated non-stop for approximately 3 hours and travelled a distance of 2.5 kms over 2 days.

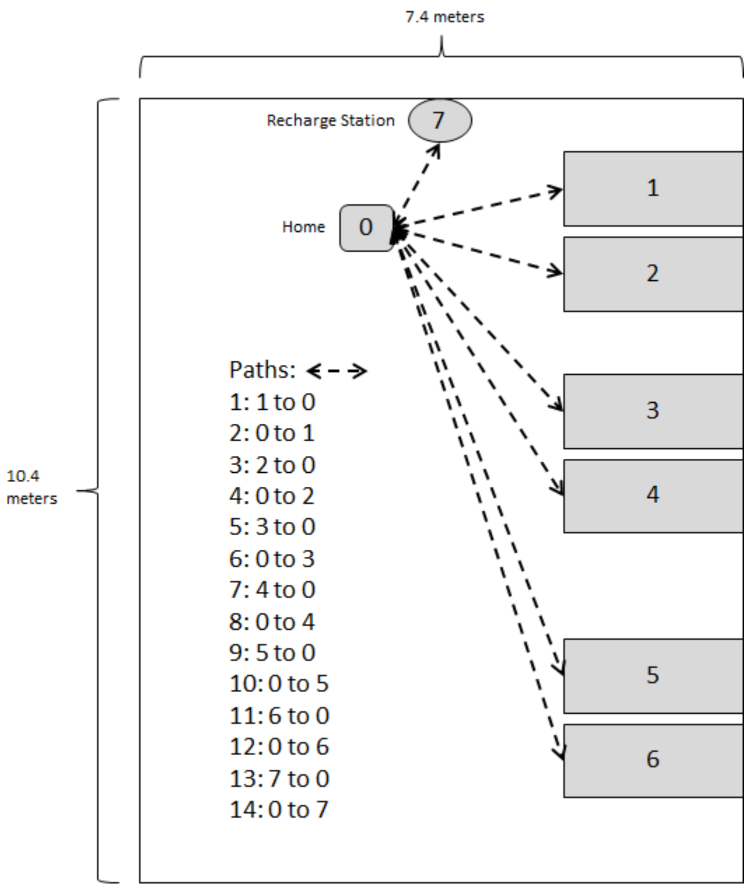


Figure 4.1: Map of the Lab with navigation paths

Each navigation path between locations 0-7 was traversed 30 times each so in total the robot performed $14 \times 30 \times 2$ (2 different speeds: 320 and 220 mm/second) = 840 navigation runs. We investigated whether there were any relationships between the distance travelled by the robot and the time taken during navigation, navigation speed and power consumption of the robot in order to select the appropriate speed of the robot. During the navigation runs the researchers working the office continued with their normal work at their desks. The volume of the robot was turned to off during the navigation runs as we did not want the researchers to be disturbed by the robot's voice each time it approached the desk.

4.1.1 Results

Graph 4.2 shows the power dissipation[2] for 14 navigation paths at two different navigation speeds 320 and 220 mm/second. A Pearson product-moment correlation coefficient was computed to assess the relationship between the distance and power

[2]Power dissipation-is a measure of the rate at which energy is dissipated, or lost, from an electrical system.

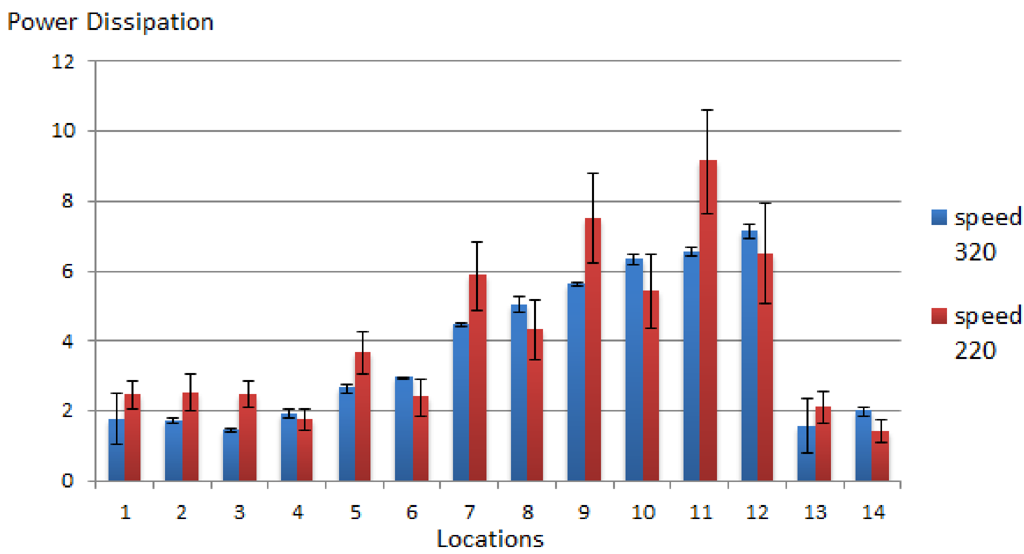


Figure 4.2: Power dissipation Vs Speed graph

dissipation. As expected there was a positive correlation between the distance and power dissipation, $r = 0.804, n = 840, p = 0.000$, which indicated that the longer the distance travelled the more power is consumed. Time and power dissipation were also positively correlated, $r = 0.938, n = 840, p = 0.000$, which suggests that power consumption is higher when the robot is navigating for longer. Both distance and time are positively correlated to power consumed, which is an intuitive result.

We found that speed and power dissipation are negatively correlated $r = -0.137, n = 840, p = 0.000$ which means the lower the speed the higher is the power consumption. This is also an intuitive result as the robot will take more time to travel a path at a lower speed. Also the average power dissipation for all 14 navigation paths for a navigation speed of 220 mm/second was 4.11, 11% higher than that at a navigation speed of 320 mm/second (average power dissipation 3.66). Please note that the power dissipation values for locations 13, 14 are for runs from the home position to the charging station so the distance is shorter as shown in the Figure 4.1.

During the navigation runs, the robot had to be recharged 11 times as the battery voltage became low. The voltage level was recorded when the robot became non-operational: this voltage reading was 11.20 Volts averaged over 11 occasions. The battery voltage recorded for a full recharge was 13.60 Volts average (indicated by the green led light on the charger), also the average recharge time was 2.5 hours. Average CPU usage during navigation runs was 33.67%. So navigation consumed a third of computation resources on the robot.

We also asked the 5 office co-workers after the experiment a feedback about how they perceived the navigation of the robot running based on two factors, the noise made by the robot and the speed of the robot. The informal feedback received from them suggested that, faster navigation speed (320 mm/second) was more uncomfortable than a slower navigation speed of 220 mm/second for these sets of users. This result is also similar to a study by Butler et al. [165], which indicated that the human subjects were comfortable with speeds were between 250 mm/sec and 380 mm/sec (slower that normal walking speed.) Also the noise made by the sonar scanner on the robot was disturbing especially when the robot approached them near their desk while they were working.

We analysed the power dissipation, speed and time relations in order to understand the relationship between them. We envisaged that this will allow us to decide the appropriate values for the navigation speed of the robot where the trade-off between power consumption and user acceptance is taken into account. We have summarised some findings from the navigation experiment as follows.

4.1.2 Findings

- **Recharge Voltage:** The robot should initiate autonomous recharging before reaching a voltage level of 11.20 V as the robot can become non-operational after the battery is too low. Also the threshold voltage value indicating full recharge should be above 13.50 V.

- **Speed:** The robot's navigation speed of 220 mm/s was more acceptable for the users as higher navigation speed (320 mm/s) made them uncomfortable. Although having a lower speed of of 220 mm/s would mean slightly more power (11% higher than a speed of 320 mm/s) consumed by the robot.

- **Noise:** The robot's sonar sensor noise (Ultrasonic sensors emit a sound pulse, ticking sound) disturbed the users, ideally the robot could switch off the sonar sensors used for obstacle avoidance after arriving at the desk and at home position as obstacle avoidance is no longer necessary when the robot is not moving.

These findings were used to adapt our approach and we implemented changes to the system on speed (set to 220 mm/s for normal navigation), noise (sonar sensor switched off after navigation complete) and recharge threshold voltage (set to 12.00 V) and full recharge voltage threshold set to 13.50 V.

4.2 Long-term Pilot Study

With a revised system following the navigation experiment, we performed a pilot study with the TB in the wild to explore feasibility and understand technical issues during long-term operation. We performed a study for two weeks with existing team members in the office in March 2012. This study was an auto-ethnographic approach [166] in studying living with the TB to gain insight into design considerations and further refinements required. The office had 6 participants who continued with their normal routine work (Figure 4.3). The robot performed tasks like greeting them when they arrived in office, passing messages left by other team members, giving them reminders (from their Google calendars), auto-recharge, carry the phone etc. (the full tasks is summarised in the following Table 4.1).

Nr.	**Task Name**	**Task Description**
1.	*navigateHome*	Navigate from interaction position (desk) to home (default) position after the task
2.	*dock*	Navigate and dock to the charging station when the battery is low
3.	*undock*	Undock from the charging station to home position when battery is charged
4.	remindOnMissedPhoneCall (NS)	Remind the user to check the phone for a missed call
5.	deliverMessage (NS)	Deliver a message left by a user/guest to a designated user in the office
6.	eventReminder (NS)	Remind the user of an upcoming event from their Google calendar
7.	logBookReminder (NS)	Remind the user to fill in daily diary
8.	greet (NS)	Greet the user when they first arrive in the office during a day
9.	makeRemark (NS)	Make small talk; e.g., "How is the weather today?"
10.	deliverPhone (NS)	Deliver phone (placed on the robot) when it starts to ring to the nearest user in the office
11.	ReplyWhereAbout	Tell the user where other users are (if they have specified so to the robot)

Table 4.1: Tasks for the TB. The tasks marked (NS) involves the robot navigating to a user's desk and speaking (TTS). The tasks numbered 1-3 are the system maintenance tasks and rest 4-11 are service tasks.

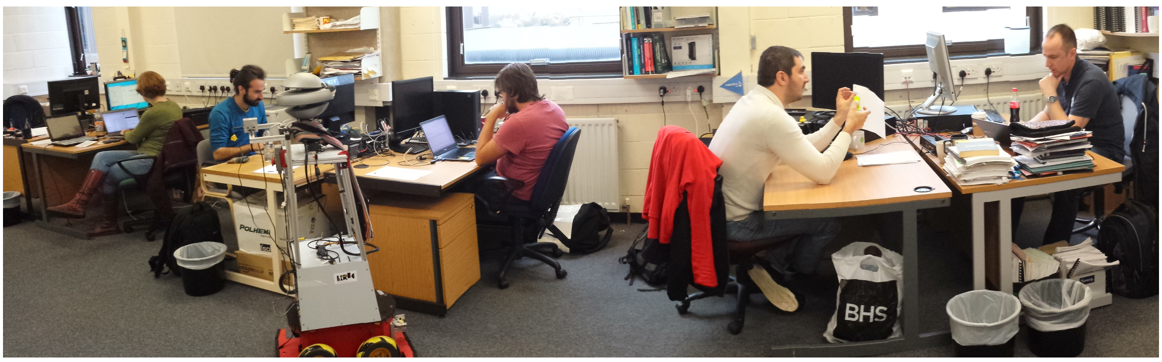


Figure 4.3: Users at the work desks with the robot (not the actual participants in the study).

During the 10 days (weekends excluded) the robot performed a total of 249 tasks (average 25 tasks/day) with an average active time (when the robot was running) of 7 hours/day. Figure 4.4 summarises the tasks performed by the robot for 10 days and the task summary can be seen in Figure 4.5. The robot was running autonomously for 10 days during this study and had 7 breakdowns due to lost navigation and 6 due to docking failure (total 13 failures). The system was restarted on each session and the TB was back in operation within 5 minutes.

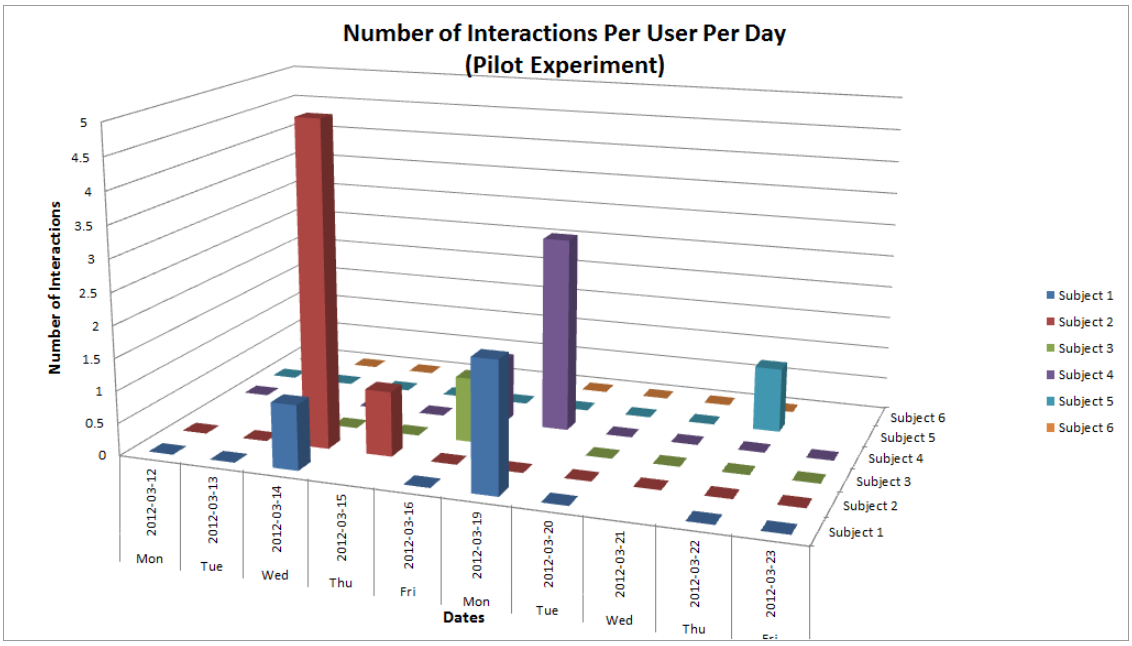


Figure 4.4: Tasks performed per subject (1-6)

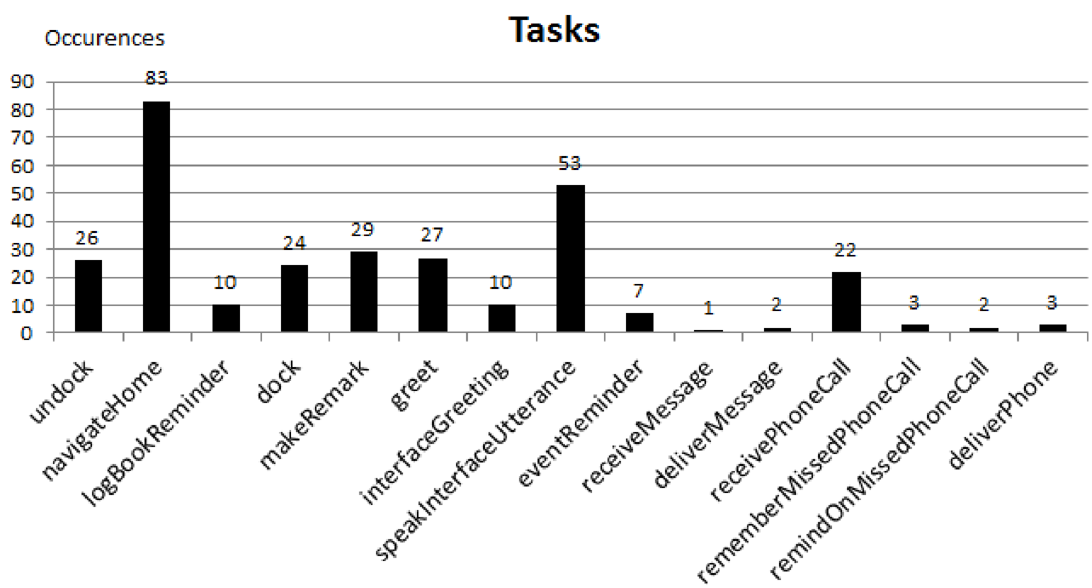


Figure 4.5: Tasks Plot

The activity log showed that out of the total available time, 240 hours (10 days) the robot was active for 70 hours (time when users were present in the office), but the total time spent during task performance was only 2.7 hours (3.8% of total active time) and home position (49.2%) while recharging took 33.5 hours (47% of total active time when the robot was not recharging) as shown in Figure 4.6.

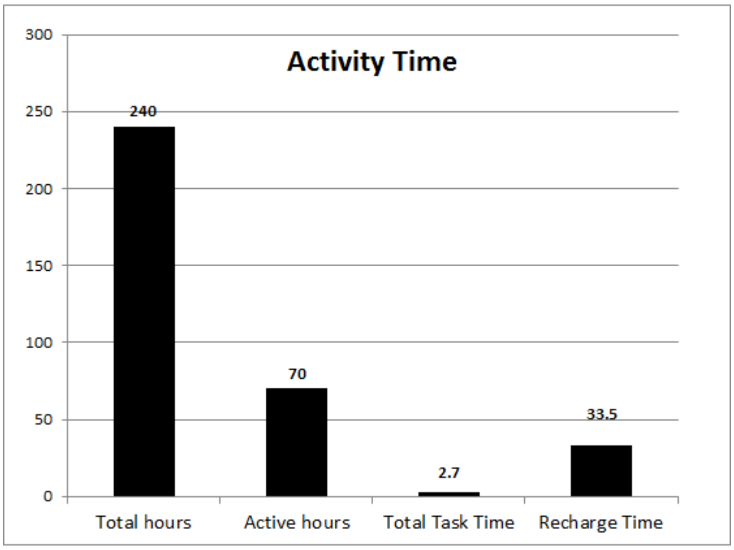


Figure 4.6: Activity Plot

The results from this pilot experiment indicate that the robot spent most of the time recharging and unavailable to perform tasks. The feedback received from the participants indicated that TB's unavailability to perform tasks during recharge was certainly not desirable and led to disappointment with the TB. The actual interactions declined over time (refer Figure 4.4) suggesting that participants were less motivated to interact with the TB as time passed. The decline in interaction could also have been a result of to 3 out of the 6 participants were part of LIREC project research team and due to lack of novelty factor [112, 111].

4.2.1 Participants feedback

The following questions were posed at the end of the experiment based on their interaction experience with TB, all of their answers are described for each question asked to the 5 participants (P1-P5).

1. What was the best aspect of the robot?

   P1: "*The robot did manage to navigate to desired location in the lab, also did manage to put itself for charging without the need of anyone from office helping it to do so*".

   P2: "*The amusement value when it started moving to see what it was going to do*".

P3: "*Provides reminder on Google calendar events*".

P4: "*Curiosity about what it is going to do once it starts moving*".

P5: "*It was reminders and comments it gave to me, only when it was working properly*".

For the best aspect of the TB, 3 out of 5 participants pointed to movement of the TB, the other 2 described tasks such as reminders and remarks made by TB as the best aspect.

2. What was the worst aspect of the robot?

   P1: "*Charging most of the time*".

   P2: "*I am not sure if there was a worse feature, it was a bit disappointing sometimes to see it had to charge itself so often*".

   P3: "*Limited tasks and interaction*".

   P4: "*The robot spent too much time recharging itself and was less active in the office*".

   P5: "*The interaction and the feedback modalities. They were not inviting and mostly also confusing. Also the nose camera gave me a bad feeling*".

   For the worst aspect 3 out of 5 participants pointed to charging as the worst aspect and 2 pointed to limited tasks provided by TB as the worst aspect.

3. Other Comments: P1:"*Teambuddy never asked to be charged it does that by itself now. Team buddy should indicate before going to recharging as there is not way to tell when it cannot be used*".
   P3:"*The robot spoke out loud in the office when I answered the remark question which makes me uncomfortable*".

For other comments, only 2 participants answered the question, one indicating verbal notification by the TB while it was going to recharging. The other participant complained about the the loud voice of the TB while making remarks.

4.2.2 Findings

We summarised two main findings from the pilot study as follows:

- **Recharging:** The robot spent 47% of its time recharging and was unable to perform tasks during recharge. Due to the changing light conditions in the room, the visual tracking during docking behaviour sometimes failed (6 docking failures recorded), especially late in the evening when the users left the office after work and switched off the room lights. Recharging was also mentioned by the participants as the worst aspect of TB during the study (4 out of total 20 responses).

- **Recharge Voltage:** Having fixed threshold values for voltage for docking (12.00 V) and undocking (13.50 V) sometimes produced undesirable behaviour. The TB set off to recharge in middle of performing a task (7 occurrences).

4.2.3 Improvements

- **Light conditions:** The TB failed to dock itself on 6 occasions due to low light conditions at night. A small flash light was installed on the robot to solve the problem with changing light conditions. This enabled the Team buddy to track the visual feature on the charging station even in the dark (the flash light would only illuminate when docking was active). Also the visual markers (2 circles) placed on the docking station were changed to a non-reflective material so that the flash light did not cause reflection from the markers. It is important for a social robot in workplaces to be able to recharge in all possible times of the day or night with varying light conditions.

- **Recharge Voltage:** Fuzzy logic was implemented to indicate the voltage levels ranging from low to full (refer Figure 4.7). We anticipated that using fuzzy logic rather than absolute voltage thresholds would provide a better approximation of the battery level [167]. So the robot would initiate recharge/docking when the battery was in low (fuzzy label) and undock when the battery was full (full for fuzzy label). Using fuzzy values also eliminated the undesirable behaviour produced by the robot during performing a task. This is described in more detail in the next Chapter 5.

- **Power management:** While the TB was recharging, we also observed that it was taking a long time for the battery to fully recharge (average recharge time was 2 hours). So we implemented a strategy where the robot, after a successful dock, would shut down hardware components (using relay switches) which included the robot head power supply (14V, 2 amp), robot navigation/motors (12V, 1 amp), stargazer navigation sensor (12V, 500 milliamp). The PC on the robot stayed switched on. We envisaged that shutting down some components not required while recharging would reduce the recharging time [68]. This is also described in more detail in the next Chapter 5.

- **Verbal transparency to indicate recharge:** The feedback received from users when the TB was about to recharge, for example one participant said, *"Team buddy should indicate before going to recharging as there is not way to*

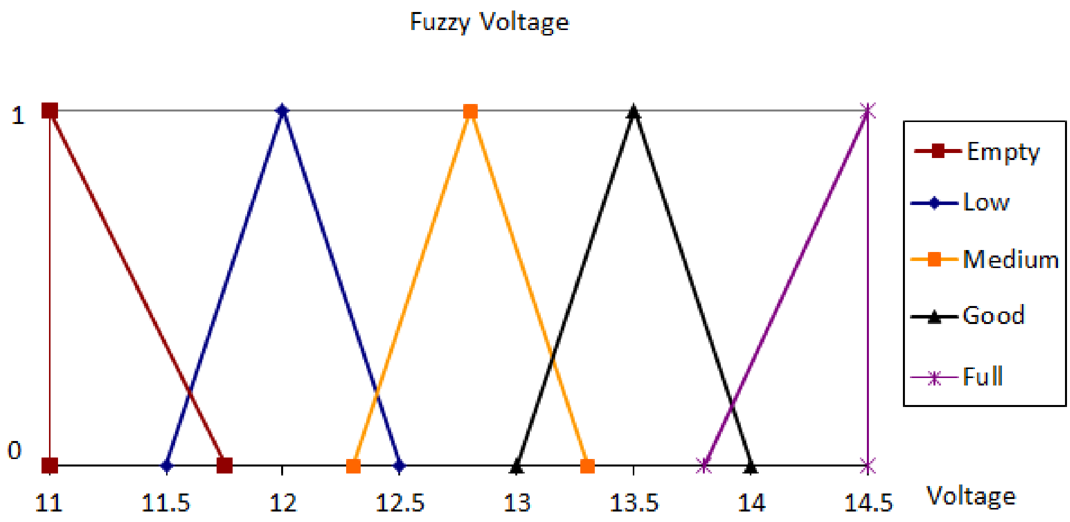


Figure 4.7: Fuzzy Voltage

tell when it cannot be used". We implemented a behaviour where the robot would demonstrate more verbal transparency [15, 35], notifying the users about its recharge intentions by saying (TTS), *"I am hungry now, i need to recharge"*.

4.3 Summary

The navigation experiment allowed us to understand the power consumption in relation to speed, distance and time during navigation of the robot. Power consumption was positively correlated with distance and time, but negatively correlated with navigation speed. The noise from the sonar scanner and the higher speed of the robot made the participants uncomfortable, and these were therefore modified in order to be more socially acceptable. The experiment also established good charge/recharge voltages and speed settings for the TB. The navigation runs also helped to validate the robustness of the navigation approach as required for long-term operation of the robot.

The long-term pilot study tested the robustness of the overall system. Recharging took a long time and the robot spent around 47% of its time in recharging activity. This was not liked by the participants. The feedback received from the participants resulted in improving the system, especially the recharge behaviour, adding verbal transparency to the TB. Some practical issues like the changing light conditions in the room were highlighted. Installing a flash light on the robot helped to resolve this problem. Using fuzzy logic for battery voltage indication provided a better approximation about the battery levels (described in next chapter 5). Shutting down system components upon identification of a successful dock would result in a faster and more efficient recharging cycle time.

The results from the navigation experiment and the pilot study resulted in modifications in the TB's functionalities. It is important to take into account not just the technical challenges but also the social issues while developing social mobile robots for long-term operation. Systematic modifications were made to our robot taking into account both the social and technical issues raised during these experiments. These improvements further enhanced our approach and assisted to develop a more robust recharge mechanism vital for the long-term operation of the robot covered in next Chapter 5.

Chapter 5

Long-term Experiment

5.1 Introduction

After the pilot study described in previous Chapter 4, a long-term study with the TB was conducted with 5 participants. The aim of the study for the LIREC project was to investigate the long-term implications when the robot was in a natural setting for an extended period of time. The aim for this thesis was to establish how the recharge behaviour of the robot was perceived over long-term interaction. TB operated continuously in an office environment for three weeks (weekends excluded), interacting with five participants. The analysis of such a long-term experiment is a big challenge [168]. Current social robotics research mostly deals with long-term interaction as repeated interactions on a fixed task (e.g. [23, 125]). In this study we investigated a continuous interaction with multiple tasks performed by the robot over the three weeks. We first start with describing our methodology in Section 5.2 where we explain the evaluation plan, study set-up and the participants for this study. Then we describe our analysis in Section 5.3, analysis was carried out on the data collected from questionnaires and system logs. Followed by some design recommendations in Section 5.4 and concluding remarks in Section 5.5.

5.2 Methodology

The study combined quantitative questionnaires, TB tasks and activity logging, along with a user diary to record their daily experiences with the robot. We used a combination of several data collection methods (Sung et al. [117]) to gain deeper, qualitative, insights in user attitudes toward the robot, and their experiences. Pre, mid and post-interviews were conducted over Skype[1] with the individual participants as well. The focus of the interviews was on functionality, privacy, information sharing, everyday

[1]Due to logistical reasons Skype interviews were conducted by LIREC project colleagues based in a different country.

experiences and their effect on human-human interactions in the office, perceptions of companionship with Team Buddy and their relation to pre-existing expectations about the robot. At the start of the study, the participants signed an informed consent agreeing to be video recorded, interviewed and to answer questionnaires during the study. The first interview was conducted before the study began but after the instructions, the second was carried out after one week, and the last interview was conducted after the study was finished. The participants also filled in three questionnaires: one before the study, one after one week, and one after the end of the study. The evaluation plan is explained as follows:

Evaluation plan:

- Before the study (Day 1):
  - Consent form: Consent to record videos and questionnaires
  - Introduction of TB: Instructions on how to use the TB
- Questionnaires
  - Demographics (Pre-questionnaire only)
  - User personality (Pre-questionnaire only, TIPI [169]).
  - Attitude toward robots in general (NARS [170], pre, mid and post)
  - Trust and confidentiality: Information sharing [171], pre, mid and post.
  - Acceptability of the TB shared with colleagues.
- Pre, Mid & Post-interview (Skype)
  - TB charging behaviour.
  - Trust and confidentiality: Information sharing
  - Functionality of the TB.
  - Privacy issues.
- Diary: Participants recorded day to day events and memorable moments.

From the study the LIREC project wanted to explore the effects of long-term exposure of TB to normal office workers. We in this thesis in particular wanted to investigate their perception about the TB's recharge behaviour. The behaviour of the TB did not change over time; rather, the TB performed the same tasks throughout the study. Our hypothesis for the study was:

- Hypothesis- *H1: The participants will recognise a degradation in service when the robot goes to recharging and the recharging behaviour of the robot will have a negative impact on user's perception of the robot.*

5.2.1 Setup

A diagram of the office environment for this study is shown in Figure 5.1. As shown in the image, there were six workplaces (labelled 1-6); note that a maximum of five participants were present at any one time. All of the workplaces were equipped with a desktop computer, along with a webcam used to detect user's presence (described in Chapter 3 Section 3.8). The robot was capable of navigating to all workplaces, as well as to its home position (label 0 in the figure) and to its charging station (label 7).

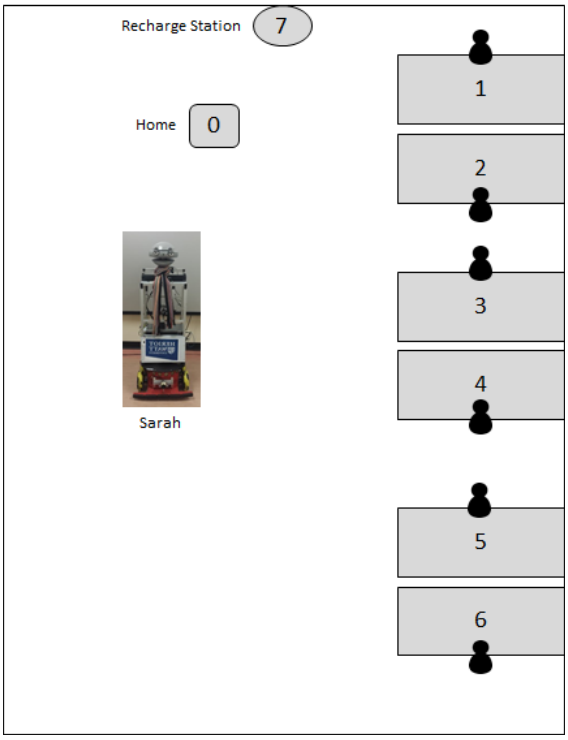


Figure 5.1: The office layout for the study. Positions labelled 1-6 are workspaces equipped with desktop computers; label 0 shows the home position of the robot; label 7 shows the charging station.

Tasks: TB was able to greet participants when they arrived in office, deliver messages left by visitors/fellow participants, give reminders about events (from their Google calendars), carry a phone placed on its body to a user's desk, navigate to their workspace autonomously and engage in a limited social interaction by asking pre-programmed questions (these questions changed every day). The TB was also able to autonomously recharge its battery if the battery level went below a set threshold (battery low). In Chapter 3- Table 3.2 we summarised the tasks the TB could perform.

5.2.2 Participants

Five participants were recruited for the study, all of whom moved their workspace to the TB's office for three weeks. The recruited participants were two females and three males aged 51, 40, 26, 22, 28 (mean age 33), 2 of them were staff employees and the other 3 were PhD students at the university. The participants had never interacted with the TB before. The office hours varied between the participants, each was present in the office between 3-5 days a week. All participants carried on with their normal work routine during the study. At the start of the study, all the participants were briefed about the capabilities of the TB (who was introduced as "Sarah") and were shown how to use the robot and the tablet interface.

5.3 Analysis

We gathered four forms of data during this study: robot system logs, user diary entries, responses to the questionnaires (mid-, and post-study) and interview responses (also pre-, mid-, and post-study). We discuss the main results of each analysis below. Some results may not be directly related to the recharging activity of the TB. However we believe that these results show some interesting findings in relation to long-term HRI in office settings.

5.3.1 Robot System Logs

We collected system log files from robot, they contain information such as TB's activity time, distance travelled, tasks performed, electric power consumption etc. The tasks Sarah performed during the three weeks of the study are summarised in Figure 5.2. The robot travelled a total distance of 1.35 kms in 15 days (average 90 meters/day). TB performed 621 tasks in total (average 41 tasks/day); each task took 1 minute on average to perform.

From the time logged for each activity, out of the total time available; the users' presence at their desks was detected for 92 hours 27 minutes during 15 days, average 6 hours 9 minutes per day (working days, Monday-Friday). TB spent a total of 3 hours 37 minutes (3.80%) performing tasks, 39 hours 48 minutes (41.10%) idle time (standing at home position but available to perform tasks) and 52 hours 39 minutes (55.10%) while recharging. This data is summarised in Figure5.3; note that the time scale on the Y-axis has been normalised on users' presence time in the office.

Each recharge session took 66 minutes on average and the TB came out of the docking station to the home position after the recharge was complete. The robot was available for an average time of 2 hours 39 minutes per day, and was recharging for 3 hours 30 minutes per day. In total, the TB spent more than half (55.10%) of the time recharging and was unavailable to perform tasks or demonstrate social presence during that time. In total, the robot operated autonomously for a period of three weeks without major technical difficulties, except for five breakdowns due to lost

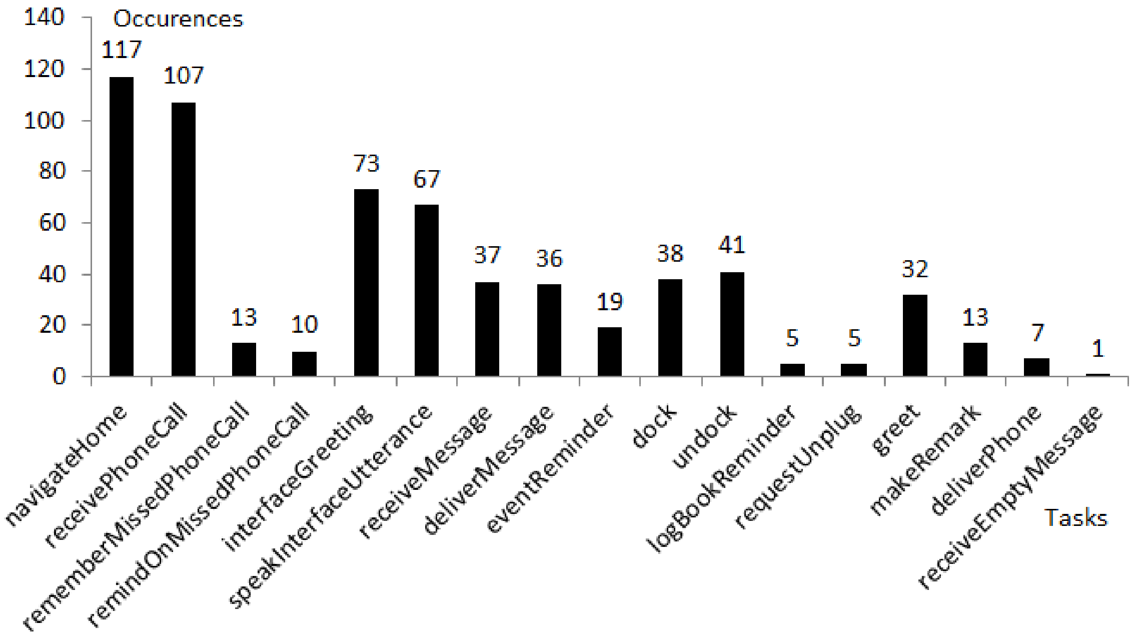


Figure 5.2: Task occurrences summary, Total tasks: 621

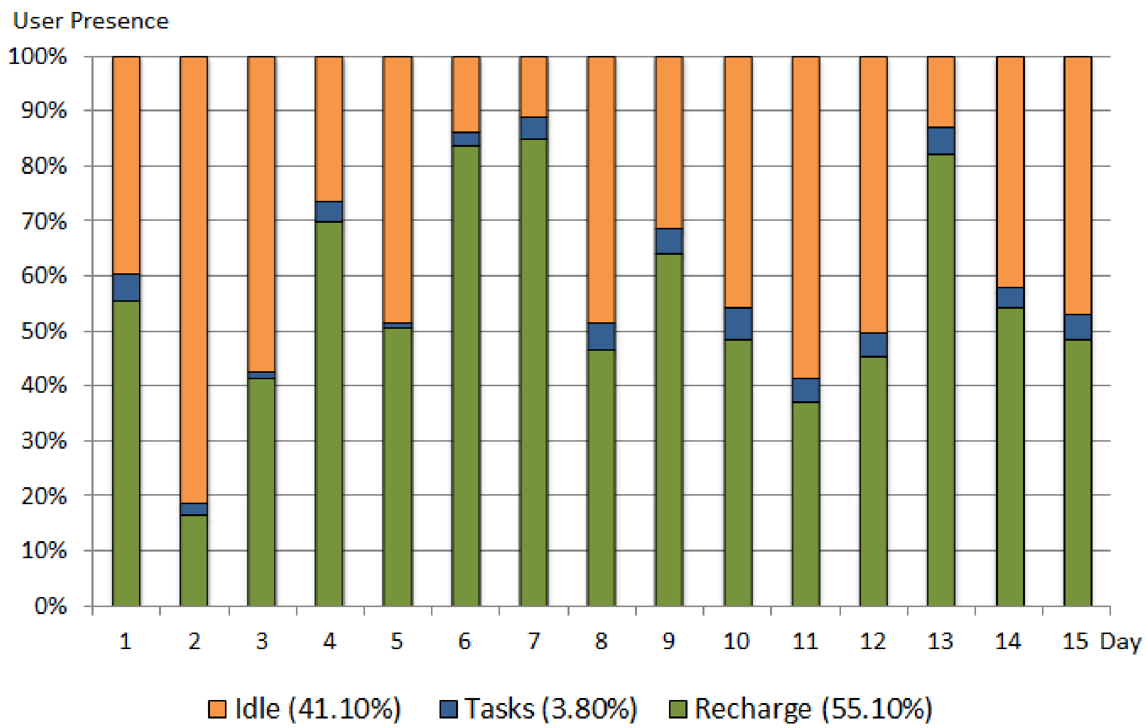


Figure 5.3: Activity time Summary for 15 days

navigation (stargazer hardware failure), and one due to an operating system update. Each time there was a breakdown, the participants pressed the emergency stop button placed on the robot and reported the problem to our team member (present in the same building but not in the same room), who was able to fix the problem and have the robot back and running within approximately 10 minutes. So there were no long-term disruptions during the study.

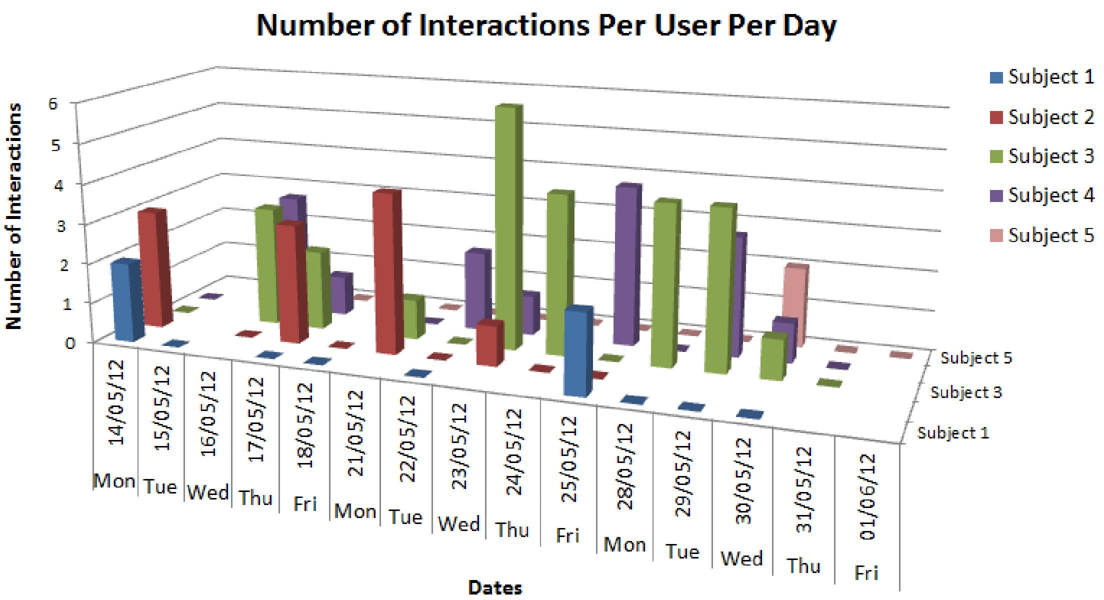


Figure 5.4: Interaction Summary for 15 days

Figure 5.4 shows the interaction summary per participant for each of the 15 days. Some participants had more interactions with the TB. There were differences in the number of interactions each participant initiated. These differences may have been due to the fact that some perhaps were present in the office for less time as compared to others. We also observed from the questionnaires and interviews that some participants (subject 2, 3) were more enthusiastic in creating tasks for the TB for fun, for example deliver messages (tongue twister, snacks) to other colleagues, hence they had more interactions with the TB as shown in the graph.

The improvements made to the system after the pilot experiment, presented in previous Chapter 4, Section 4.2.3 showed positive impact. For example installing a small flash light on the robot, helped it to find the charging station in the dark (the pilot study had 6 occurrences of docking failures due to changing light conditions in the room), there was only one docking failure during this study. Using Fuzzy logic for reporting voltage avoided undesirable behaviour produced by the robot during task performance (no reports). The power management routine in which the robot after a successful dock would shut down hardware components, reduced the average recharge time by nearly 50% to one hour/recharge session (average recharge time was 2 hours during pilot study). Overall the system was more robust (total 5 failures, 1 docking, 4 lost navigation due to stargazer hardware failure) in comparison to the pilot experiment (total 13 failures in two weeks run, 6 docking, 7 lost navigation due to stargazer hardware failure).

5.3.2 Interviews

Skype interviews, pre, mid and post-questionnaires were combined to gain more insight about the interactions between the TB and its users. The LIREC project investigated the manner in which attitudes towards the office companion changed over time. The first interview was conducted before the study began, the second was done after one week and the last interview was conducted in the end of the study. The interviews were open ended and participants were asked general questions about their experience with TB in relation to recharge, functionality, information sharing and privacy. All interviews were audio recorded and transcribed later for analysis. The interviews and their transcriptions was performed by LIREC project partners, but the analysis was done in this thesis work. Most of the conversation were free flowing natural conversation based on some generic questions asked about their experience and interaction with the robot. Some questions asked to the participants during the interview are listed below.

- Q1: How has it been to have a robot active in the office?
- Q2: So have you been talking to the colleagues around the office about the Teambuddy?
- Q3: So do you think you've learnt everything you can about the team, about the robot?
- Q4: Do you think you understand how the robot navigates and finds people?
- Q5: Do you have any routines in taking care of Teambuddy?
- Q6: Do you feel Teambuddy is a companion?
- Q7: Do you kind of think Teambuddy has lived up to your expectations?
- Q8: How would you describe the TB, would you say it's a friend or a pet or an office assistant?
- Q9: Do you go up to Teambuddy to interact with it, or does she mostly come to you?
- Q10: Do you find TB disturbing at all when you're working?
- Q11: How about the charging, have you been thinking about the charging?
- Q12: Do you think you'll miss having it around once the study is over?

Week 1: First contact

These were short interviews just to get to know how the participants were preparing for the study. The participants had a hard time knowing what to expect from the robot, as they had no experience in interacting with similar type of robots. Three of them were a bit worried that the robot might be a distraction in their work; however, they were looking forward to the study, and some users expected the robot might give the participants something to talk about with each other.

Week 2: Mid

We have summarised some responses (transcribed from interviews) from the participants with issues related to recharging during week 2 of the study. The subjects (S1-S5) are anonymised from their actual quotes from the interviews.

- S2: *"you cannot charge it you just feel, I need to go and try to help it to reach the point of charging again, and something like that. I said no, no, it wasn't emotions, I need to help it anyway. You feel that something is alive around you."*
- S4: *"This week she's doing a little bit more. Yeah, we talk about her and we have a laugh sometimes. Often she needs her batteries recharged as she sit quiet for a long time."*
- S4: *"she does greet me, sometimes though she's charging so sometimes she doesn't greet me until much later on".*
- S3: *"It don't seem to be such a problem any more, she charges herself quite well."*
- S1: *"She usually spends a lot of time charging, when she finished she says she is going back to work now".*
- S5: *"I think Sarah's quite automatic in her own direction, sort of like she goes and charges herself up and she just comes back, it doesn't seem to be any routine."*

The participants seemed to notice the TB's charging behaviour and all 5 participants mentioned the TB's charging behaviour during week 2 interviews.

Week 3: Post

- S1: *"I think, when over the week she spent quite a long time on the charger as well, that was something I was thinking, she does spend quite a long, a large portion of the day being charged up."*

- S3: *"I felt it (TB) was no longer predictable so I thought oh there's no point. There were definitely messages and there were calendar messages that she didn't give because sometimes, because she was on the charger."*

- S5: *"I could see that when we, when we leave messages for people, she mostly, but not always, gives them the message as soon as they come in, If she's not on the charger that is".*

- S2: *"I think there was one day when she just didn't seem to do anything at all, she was just sort of plugged into, she did very little, she was just plugged in to her charger, I think she's having a bad day. Just having a boring day."*

- S4: *"Yeah, it's boring when it's just charging there."*

- S5: *"when she's charging, it is quite an effort to every time go and interact with the tablet when I'm just going to get a coffee.."*

- S3: *"I think what was particular frustrating, and I think I would probably speak for most of us in the room, is that she's spends so long of her day charging."*

- S3: *"It was just hours and hours of charging, and then she would, she go around passing off messages and then go back to the charge and it was kind of a bit frustrating."*

- S4: *"It's like, why can't you (TB) prioritise and give me all the messages and all your information in one go, because she's wasting a lot of her, you know, then very very quickly after she's done that, then she needs to do charge again because she's run out of power. So it's like..., oh you silly Sarah."*

- S2: *"It wasn't disturbing it was just a bit annoying, you know what I mean, I'm in the latter end of the study, certainly the last few days I wasn't quite as busy in terms or work and I was more up for playing with Sarah and getting involved with her, but every time I was ready to do that she was too busy charging."*

- S1: *"the other time she went on charge for three hours and delivered it four hours later. So you just had no idea. So it made you feel like what's the point in giving her a funny message for somebody or even a message, because you had no idea when she was going to deliver it."*

- S2: *"I did, I managed to get her to deliver the things when she wasn't charging, I got her to say some funny things like exterminate, exterminate to X and we had a bit of fun you know."*

- S4: *"Yes I would do (the study) it again, it would be good if she was just a little bit tighter, you know, she didn't have to charge so much and a few more personalised messages and she learnt quicker."*

- S4: *"I was kind of hoping that when you have a guest in, so a number of people from my office came to visit, because they wanted to have a look at Sarah, just would have been nice, if we could have pressed the button and she could have done a few things, but she just, most of the times she was charging or she was just sitting there. It would have been nice if she'd acknowledged the guest, said good morning or something, I don't know..."*

After the study week 3 interviews, all the participants said that TB spent a lot of time charging which they found boring. All participants appeared to be more critical about the charging behaviour of the TB.

5.3.3 Sentiment Analysis

We performed sentiment analysis on the all the responses obtained from the interview data [175]. Sentiment analysis, also known as opinion mining, is the task of identifying opinions expressed in texts and whether the expressions indicate positive or negative opinions toward a subject or topic (Nasukawa & Yi, [172]). According to Nasukawa and Yi, sentiment analysis involves the identification of sentiment expressions, polarity and strength of the expressions, and the relationship to the subject or topic. There are a number of different methods and tools with which to conduct a sentiment analysis. There is no clear agreement as to which method and tool is the best. For our analysis we chose a tool called Semantria. Semantria is a sentiment analysis solution created by Lexalytics Inc.[2], a well-known text analysis software provider. The sentiment software application Semantria (www.semantria.com) offers a fee-based Excel plug-in that enables the analysis of Excel spreadsheets according to positive, neutral and negative sentiments.

The Semantria Excel plug-in conducts an automated sentiment analysis of the dataset based on algorithms developed to extract sentiment in a similar manner as human beings According to Semantria[3]. The extraction of sentiments in a document adheres to the following steps; (1) document broken into parts of speech (POS) tags, (2) algorithm identifies sentiment-bearing phrases, (3) logarithmic scale from -10 to 10 scores each sentiment bearing phrase, (4) scores combined to determine overall sentiment. Through these statistical inferences, each sentence is tagged with a numerical sentiment value ranging from -1.0 to +1.0 and a polarity of (i) positive; (ii)

[2] `https://www.lexalytics.com/`
[3] `https://www.lexalytics.com/resources`

neutral; or (iii) negative. Since its launch in 2011, a number of businesses and researchers have used Semantria to conduct sentiment analysis (Aston, Liddle & Hu [173], Abeywardena [174]).

We stripped the interview document and separated out the interviewers comments and participants responses into separate Excel files using a script. This transcribed document had over 2000 sentences[4]. Using the tool Semantria we ran through the participant responses to generate sentiment scores for each response. Overall from a total 440 participant responses, we performed a keyword search using keywords *"recharging"*, *"charging"*, *"charge"*, *"charg"*, *"recharg"* to see what sentiment score the tool gave us to that response. We have provided the results below in Table 5.1.

Sentiment	Total	Recharging Related	Recharging %
Positive	227	5	2.20
Negative	109	25	22.93
Neutral	104	8	7.69
Total	**440**	**38**	**8.63**

Table 5.1: Sentiment Analysis Results

Out of total 440 participant responses, recharging was mentioned 8.63% (38) times, and 22.93% (25) of total 109 negative comments were recharging related, 2.20 % (5) positive and 7.69 % (8) neutral. Figure 5.5 shows the sentiment for recharging related responses with total responses for each sentiment.

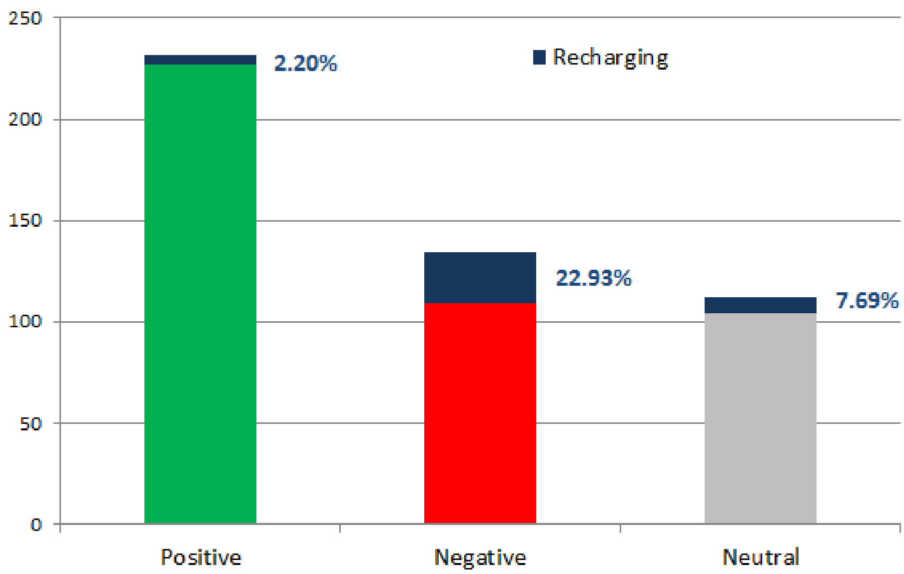


Figure 5.5: Recharge Sentiment, Y-axis: number of responses

[4]Full transcription of interviews can be seen at: `http://www.macs.hw.ac.uk/~amol/download/phd/InterviewTranscription.pdf`

And total of 38 comments made regarding recharging, 65% (25) were negative, 13% (5) positive and 22% (8) were neutral. Figure 5.6 shows the overall sentiment breakdown and on the top right sentiment breakdown for recharging for positive, negative and neutral responses.

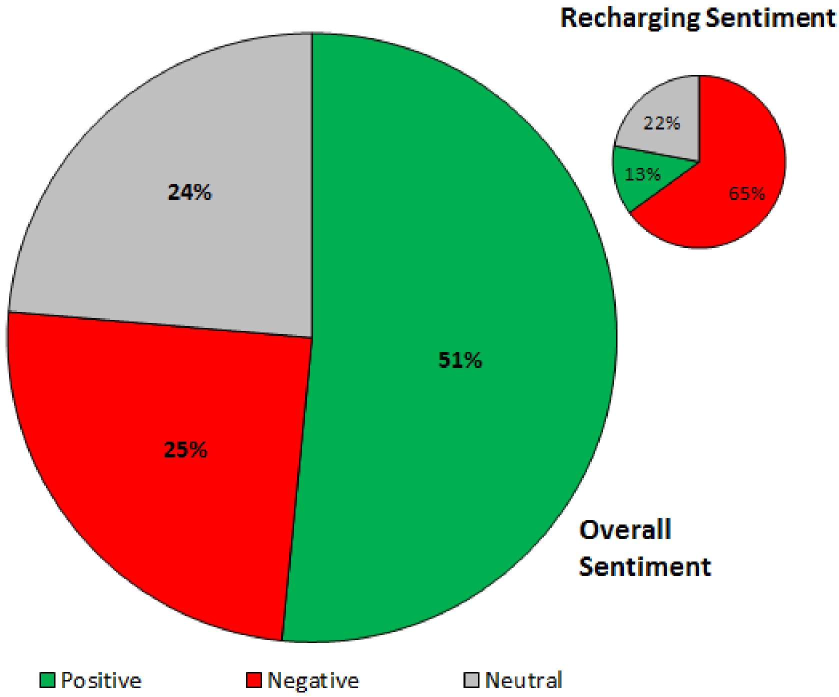


Figure 5.6: Overall Sentiment Breakdown (%), Top right recharge sentiment (%)

Also out of the 25 negative comments related to recharging, 8 were mentioned in the second week of the study and 17 during the third week. So it seems, the participant's frustration about recharging grew over time. In a previous study Fernaeus et al. [115] reported study with Pleo, a robotic toy dinosaur, the families that interacted with Pleo reported issues with the battery recharge and how their frustration grew over the long-term. A similar effect was observed in our study where the participants frustration about recharge grew over time and they seem to report more negative things about the TB's recharge during their interviews supporting our hypothesis *H1*. Moreover, there were only 6 occasions where the interviewer had actually asked a direct question about recharging, the participants were spontaneous commenting about recharging. We have listed the 6 questions related to recharging asked by the interviewer below.

- *"And how about the charging, have you been thinking about the charging?"*
- *"Yeah, so that it charges in the right place?"*
- *"Have you thought about the charging at all. Has it been problematic ?"*
- *"So you were saying in the beginning about the charging?"*

- *“Does she have a certain charging pattern?”*
- *“But then, were you ever able to play with her when she wasn’t charging?”*

Figure 5.7 describes the word cloud from all responses generated by Semantria, negative words shown in red and positive words shown in green.

Figure 5.7: Word Cloud: Positive (Green) and Negative words (Red)

5.3.4 User diaries

Participants were asked to fill in a daily diary to write down their daily experiences with TB. Although not all participants filled in the diary regularly. At the start of the study, some participants were concerned about TB’s behaviour especially its stare; for example one participant wrote on day 1: *“Felt a little freaky having her in the room. Not sure I like being alone with her. It feels a bit strange and possibly a bit scary as i have no idea what she can and cannot do”*. The following descriptions are derived from the diary entries based on the questions asked to them.

Q) What did Sarah do that the participants find helpful?

- Delivering snacks, delivering messages.

Q) What did Sarah do that stood out to the participants during the experiment (funny, stupid, strange etc.)?

Positive: Delivering tongue twister, bringing snacks, telling the participants that the TB will miss them (this was a remark made by TB on last day of the study), offering them snacks.

Negative: Charging itself for a long time, parking itself at the participants’ desks from time to time, staring at the participants (which some found disturbing),

Q) Who did the participant talk about Sarah with? And what about?

- Discussed Sarah with family and friends, filmed Sarah in action to show to family and friends, Facebooked on Sarah and replying to her messages.

From the user diaries, the participants found the TB useful with some tasks like delivering messages, snacks, but they did not like the TB's recharge routine. So the findings from user diaries on TB's recharge was reported negatively supporting our hypothesis *H1*.

5.3.5 Other Findings

From the analysis on the data collected from questionnaires, interviews and user diary we summarise other findings in this Section.

Questionnaires

The participants were asked to rate each questionnaire item on a 5-point Likert scales (1-Strongly Disagree, 2-Disagree, 3-Neutral, 4-Agree, 5-Strongly Agree). Figure 5.8 presents the average ratings given by the participants on the mid- and post-study questionnaires[5].

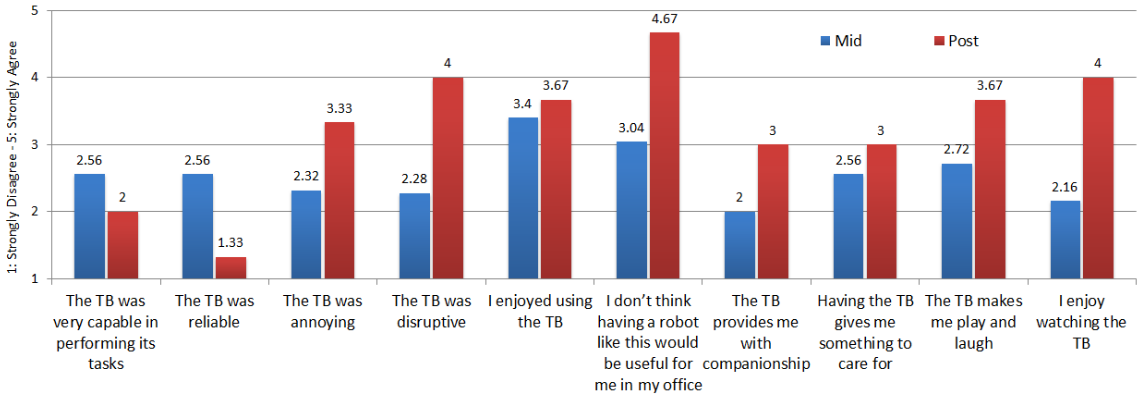


Figure 5.8: Questionnaire Summary

From the mid (after one week), post (after week 3, end of study) questionnaire scores given by the participants, there were differences in average ratings over time. The ratings for the TB's capability of task performance and reliability decreased over time. Participants also perceived that the TB became more annoying and disruptive over time. The effects on reliability and disruptions could also be associated with novelty effect. Previous long-term studies [108, 4, 109] have indicated that novelty effects fade over time and user's interest and engagement decreased over time. This also appears to be true in our study especially on the measures of performance, reliability and disruptions.

However, participants' enjoyment in using the TB increased slightly over time. Also participants agreed over time that the TB made them play and laugh and they

[5]Statistical tests were not conducted due to the small number of participants and two participants did not answer the post questionnaire. So post questionnaire scores are averaged for 3 participants.

enjoyed watching the TB. This result is slightly contradictory to novelty effect. We interpret that the participants during Week 2 and 3 added a new functionality to the TB to deliver snacks, jokes and tongue twister might have influenced the enjoyment factor. Also the participant mentioned these added tasks positively during the user diaries. A previous long-term study by Kanda et al. [112] with school children reported that the robot was capable of engaging children after the second week (although with a slight decay), which the authors attribute to the new capabilities implemented in the robot (the more a child interacts with the robot, the more different behaviours are produced by the robot to that child). Adding new capabilities to the robot appears to keep user's interest and engagement over time, however, these new capabilities may be limited by hardware and battery capacity of the robot.

Participants agreement towards having a robot like TB would be useful in their office decreased over time. However, participants agreed over time that the TB provided them with companionship and something to care for. Figures 5.9, 5.10 shows interaction example from images captured during an interaction.

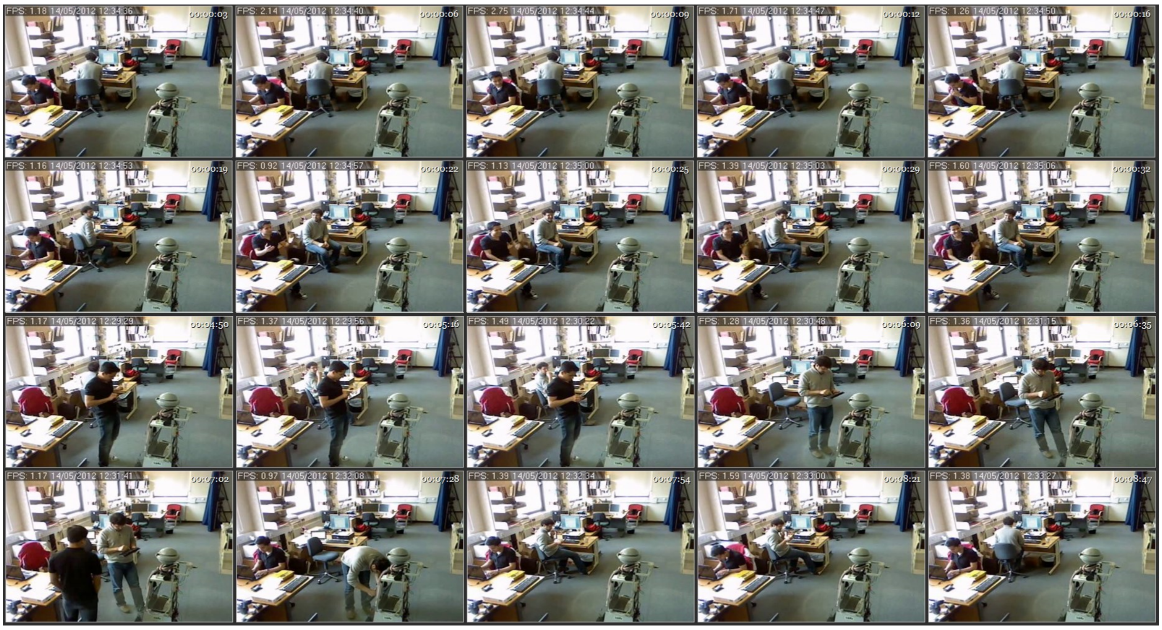


Figure 5.9: Interaction example: Room Camera preview

Functionality: Participants were critical about the flaws and expected more from the TB. They complained about the slow movement of the TB while delivering the phone. The phone delivery task was not found useful because it took too long for the robot to bring the phone over to a desk from the moment it started ringing. However, the navigation speed of the TB was same for all tasks. Indicating that having a faster navigation speed for urgent tasks like carrying the phone can be considered, but this also induces a safety risk. Participants desired an easier means of communicating with the TB. Using the tablet interface and speech recognition is often not practical. Providing users with other options for communicating such as a mobile application or

Figure 5.10: Interaction example: Robot Camera preview

website to interact/provide tasks to TB might be more useful [136]. The participants also added a new functionality to TB during the second week of the study, by adding a biscuit/snack delivery task using existing functionality. TB delivered biscuits to participants on 19 occasions during week 2 and 3 of the study. Adding flexibility to create new tasks for office robots may extend their use and make it more appealing for the users.

Four participants used the “reminder” function via Google calendar; however, one participant used other calendar programs such as Outlook Express and was not able to use this function. The participants found the delivery time of the reminders or messages problematic. Participants could never be sure when a message would be delivered depending on whether the TB was recharging at that time, it could be delivered five minutes later or the next day. One user wanted to be reminded by the robot to go home and catch a bus. She wanted to be reminded five minutes before the event, and tried to manipulate the time of the calendar reminder to achieve this. However, she mentioned during her interview that there was no way to predict when the reminder would be delivered, as the TB sometimes would miss giving calendar reminders if it was performing other tasks or it was recharging. One participant said that she was inclined not to leave important messages, and that if she did so, she would make sure that there was a back up way to deliver that message.

Overall Experience: Four participants said it was nice to have TB around and it was somewhat fun experience. They also said there is lot of potential to have an office robot like TB with improved functionality and easier means to communicate with it. One participant said *“I’ve enjoyed that, it’s been nice meeting new people, Sarah is a great way of talking to people, cause we all have a shared, something shared* *in common.".* Two participants also said they will miss TB: they even sent messages to TB saying, *" I've enjoyed working with you Sarah", "It was nice getting to know you. Love X. Keep in touch via Facebook :-)"* which indicates that there was some level of attachment that these two participants developed with the TB over the days.

Overall, the participants said that the robot has a lot of potential to become more useful. However, the participants mentioned that in the current state it takes time to understand and interact with the robot, and this was not always something that the participants had time to invest in. One participant mentioned that 3 weeks wasn't long enough to get to know Sarah properly. *"It does take a lot of time to figure Sarah out, especially with me only working part time and with her spending a lot of time being inactive on her charging station. Three weeks doesn't feel like quite enough.".* Conducting long-term studies in workplace environment is challenging due to practical and logistically reasons. However, long-term studies also provide practical feedback about the technical limitations of social robots which are sometimes hard to investigate in short time studies.

5.3.6 Discussion

One of the main issues encountered in this study was the TB's charging behaviour which to led to disappointment and disengagement by users. Criticism of the robot's recharge activity was raised 25 times during the interviews and user diaries (reported in Section 5.3.3). The TB spent a total of 55.10% of its time recharging and was unable to perform tasks or demonstrate social presence during recharge. The limitation of the TB while recharging was exposed during the study and the TB did not have any coping mechanisms/behaviour to manage/mitigate its limitation which appeared to have disappointed the participants.

Similar results were found from a study by Fernaeus et al. [115], a study with Pleo (a robotic toy dinosaur). The participants found recharging Pleo became a time-consuming activity, long recharge time frustrated both the adult and child participants. Participants did not like the fact that there was no way of telling when the robot Pleo was going to run out of battery, and the need to manually to recharge it. The authors suggested that high prior expectations were not met, which caused some participants to stop using the robot when the novelty-effect wear off and people became less and less motivated to recharge the batteries of their pet robot. A mismatch between the users' expectations and the social intelligence of the robot may negatively impact acceptance and use of the robot [176, 177].

Overall, the participants from our study found the experience fun, but a little underwhelming. They were hoping for more fun things to happen. They thought they had perhaps been a bit optimistic, as TB was did not learn much about their behaviour and spent much of the day charging. Such charging "habits" will be picked up on by users; one participant even recognised the charging pattern even though he did not know about TB's charging routine beforehand. Our Hypothesis- *H1: The participants will recognise a degradation in service when the robot goes to recharging and the recharging behaviour of the robot will have a negative impact on user's perception of the robot.* was supported in this study from analysis of questionnaires, interviews and user diaries.

We thereby interpreted that careful consideration of the recharging activity and having appropriate social mitigation strategies to manage user expectations during recharge is essential for the robot to work as an assistant robot and be socially acceptable. However, we acknowledge the fact that the social context in which this study was carried out (office environment with shared physical space) highlighted the main findings on recharge behaviour of the robot. In other social context, for example where the robot that serves as a museum guide or is shown at exhibitions, robots such as AIBO [59] and Kismet [177]. Where the only purpose of the robot is to engage people in interaction, the recharge activity may not be noticed by users, as pointed out by other long-term studies in public space environments [108, 107].

5.4 Design Recommendations

We describe some design recommendation based on our lessons learnt from long-term interaction study.

5.4.1 Autonomous Recharging

During long-term interaction with social mobile robots, the recharging activity of the robot can play a crucial role in terms of its social perception. We have some recommendations based on recharging activity for social mobile robots.

- **Selecting an appropriate recharge time:** It is critical for a mobile social robot to select an appropriate time to recharge itself as recharging can cause disruptions to the service it provides and led to disappointing the users. A mobile robot operating in a social environment can learn about its users' availability in that environment. For example it can learn over time when users are present in that social environment so as to build an expectation whether the users will be present at a given time during the day. It can use this information to intelligently plan its recharge time.

  To further illustrate on this point, we analysed data (one week) from the user monitoring module reported in Chapter 3 Section 3.8 recorded activities (entry, exit, break) of 5 users in the office. Using a data mining Apriori algorithm (developed in LIREC project [178]) using memory generalisation mechanism which learns users' activities and time relationship taking into consideration user presence. From the results, we can observe that the memory generalisation mechanism was effective in finding out the users activity patterns. The robot can learn users' presence patterns and hence adapt its actions to these patterns.

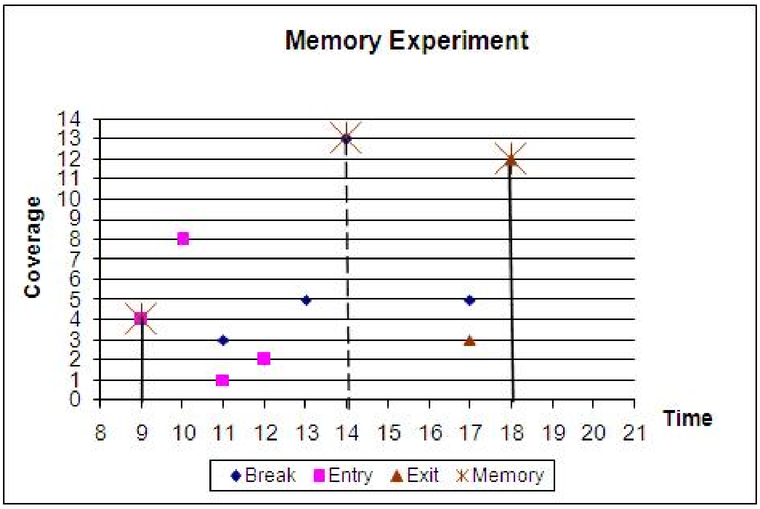


Figure 5.11: User pattern results and activity graph

The graph (Figure 5.11), illustrates the user activity coverage for each event occurred (entry, exit, break) on Y-axis on a time line on X-axis (time where no events occurred have been omitted from graph). The 3 vertical lines on the graph show the results – entry (the earliest time is chosen): 9, exit (the latest time is chosen): 18 and break: 14 (the most occurring) hours. Noticeably, the user activity coverage shows that more entry events occurred in the beginning of the day, exits at end of the day and breaks during mid-day, usually when the users left for their lunch. The learned user presence patterns can aid the robot in determining an appropriate time for a recharge session, for instance, between exit and entry time and also during break time if necessary [179]. Moreover a mobile robot can learn about its usage when users are present at given times in the day to plan its task performance more wisely [180].

- **Recharge duration:** A long recharge time can break engagement between users and robot. The recharge time could vary according to the priority (utility vs social) of pending tasks. The robot instead of doing a full recharge (takes longer time) could do a short recharge and finish its pending tasks and come back to recharging. For example a reminder task (utility task) could have a higher priority than greeting (social task) when battery is low/recharging [181].

  Although having short recharge sessions too frequently can affect the battery health of the robot [42] and type of battery used (more details mentioned on memory effect in batteries in Chapter 2 Section 2.2.1). So there is trade off between more frequent recharge sessions for shorter time (not suitable for battery health) against longer recharge session (better for battery health) where the disengagement between robot and human can be for longer time.

- **Behaviours while recharging:** The users feedback indicated negative perception of the robot's recharging behaviour. However, none of the participants appeared to be critical when the robot was sitting idle (the robot made idle motions with its head and executed eye blink) at its home position. Adding idle behaviours while recharging (verbal/non-verbal) may help to increase its perceived social presence. If a robot does not make any motion in its standby state, users may feel that the robot is being turned-off or even out of work. On the other hand, if the robots can make human-like idle motions in standby state, then they might make people feel that they are alive [128]. However using idle motions may induce more power consumption and prolong the recharge time, so the trade-off should be considered.

  Implementing the recharge behaviour as a part of social interaction can also perhaps help to manage the user's perception about the recharge of the robot. Tanaka et al. [111] (sleeping posture while recharging) and Wada and Shibata [113] (using pacifier while recharging) explored such strategies which showed positive results. Also during our study one participant said *'the robot could just as well sit at the charging station and deliver messages instead of going up to each persons desk"*. The robot could potentially perform at least verbal tasks while recharging.

- **Social positioning for recharging:** The placement of the charging station can play an important role in terms of perception of recharging activity of the robot [35]. Due to health and safety reasons the charger needs to be near a wall, so the charging station may be far away from the user. If the robot can be in sight of the user while recharging it might improve social presence. Also the position of the charging connector on the robot can dictate its orientation. In our case the due the sensor alignment required to find the visual marker, the charging connector was in front of the robot, so the robot was facing towards the wall (charging station) while recharging. This might have dis-engaged the users during our long-term study. For robots having a face/head, positioning of charging connector should thereby be given special attention, so that it can atleast face towards the users (against the wall) while recharging.

- **Use of beacons:** The auto recharging process commonly involves 3 main steps; 1) finding the charger, 2) approaching the charging station and 3) plugging into the charger (in the case of wireless charging, coming close to the charger).

Existing approaches for finding the charger commonly involve navigating to the charger using visual markers used as beacons [63, 2, 65, 66, 68, 3]. It is important that practical challenges like changing light conditions are taken into consideration while designing approaches using visual markers. In our long-term experiment installing a flash light resolved the problem with changing light conditions. The choice of sensors for finding the charging station can help to eliminate problems with light conditions, for example using a laser range finder, infra red to find a feature placed on charging station instead of using vision based approaches with camera might be useful.

5.4.2 Managing user expectations

It is important that the robot demonstrates transparency, notifying the users about its recharge intentions by either verbal or non-verbal behaviour to set the right expectation for the users. We implemented a verbal notification where the robot says, *"I am hungry now, need to recharge"*. The notification should be a part of the design process and this can vary (verbal/non-verbal) according the scenario and the setup of the social environment. In environments where the robot is shared in the same physical space with multiple users, verbal transparency seems a more viable approach as the users might not always visually see the recharge intentions of the robot when they are busy with their routine work. In addition, the robot can try to mitigate the disappointment about its shortcomings during recharge by being more transparent verbally [35] and apologetic for causing service disruptions [15, 33]. These studies have shown positive results on perception of social robots when the robot has a limitation. In Chapter 2 Section 2.1 we covered some previous work on social handling of mistakes and limitations which could be considered in the design process.

5.4.3 Power management

It is also essential for social mobile robots to manage power resources in an intelligent manner. In the social robotics domain it can be useful to have power management which can extend its operational time. We make some recommendations for power management for social robots in this Section.

- **Sensing rate:** Power savings can be achieved by adapting the sensing rate when the robot is running low on power or expects less user interaction (user is expected to be absent). We performed an experiment by varying the sensing frame rate of images acquired by the camera with our face detection algorithm. The results are intuitive, the faster is the sensing rate, the more is the the CPU usage, refer figure 5.12. Also, when the CPU usage is over a threshold the robot could use a slower frame rate to save the computational expense.

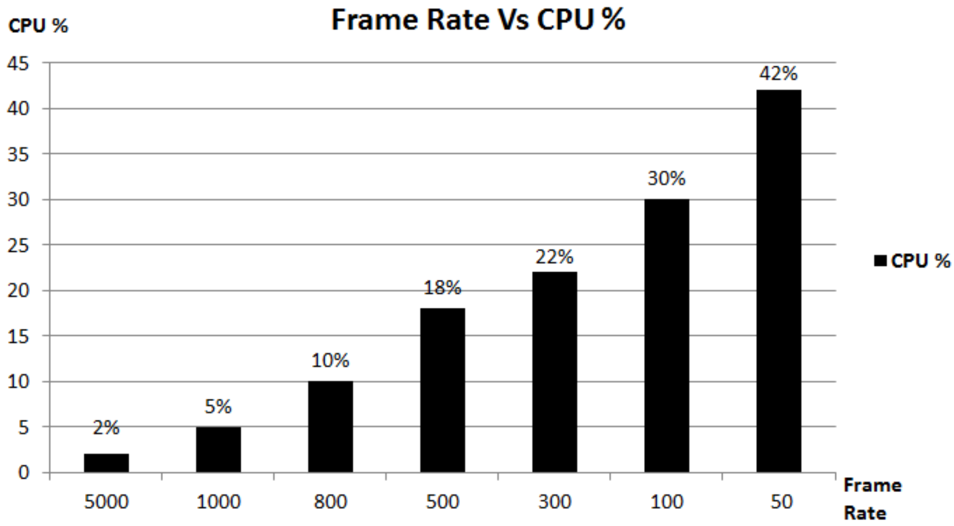


Figure 5.12: Sensor frame rate vs computation

Furthermore the robot could lower its sensing rate while moving at a slower speed. For example the speed of sensing can be proportional to the travelling speed of the robot. Also sensors used for obstacle avoidance can be switched to sleep mode while the robot is immobile or when it has finished navigating to a goal position.

- **Other power saving techniques:** Yongguo et al. suggested [182] several ways of improving energy efficiency using real-time scheduling and dynamic power management (DPM), for example, (a) Shutdown of unused components in order to avoid waste during static power in idle states [183], (b) Dynamic Voltage Scaling (DVS): dynamically changing voltage and clock frequency of a processor to save power [184]. If DPM and DVS are used and the idle state is frequent, a device may sometimes be power cycled over a very brief period of time which can consume more power as power-up requirements are greater than operating power for a device. Also the opposite is true if the determination for an idle state is not made frequently then the device may remain powered on for a long time.

  So determining the idle state for a system is critical and requires intelligent approaches especially for mobile robots. Such approaches (sleep mode) are typically used in other electronic devices such as computers and laptops [185]. Chen et al. developed a cloud based robotic multi-modal interactive computation services (RMICS) for providing the human-robot operation interfaces including the speech/sound recognition, speaker identification, face identification, sound source estimation and text to speech (TTS) [186]. Cloud based approaches can reduce some of the computation load from the robotic platform and save power on the mobile robot. Latest low-cost, single-board computers like Raspberry Pi

[187] can also provide low-power consuming alternatives to save battery life. All of these power saving approaches seem sensible and can be taken into consideration in the design process while developing social mobile robots.

5.5 Conclusion

In this Chapter we described a long-term study of an office robot companion. There have been very few long-term HRI studies with office robots in a natural setting [103, 104, 106]. The analysis from the data gathered from this long-term experiment gave some useful insights into the challenges for long-term interaction with office companion robots. Robot log activity data also indicates some key issues we need to address with regards to recharge activity of the robot. The robot in our study spent almost half the time recharging, as is the case with current state-of-the-art social mobile robots operational/recharge time (summarised in Chapter 2 Table 2.1). It became apparent that managing user expectations during recharging activity of the robot is important for the robot to be an acceptable long-term social interaction partner. We also made some design recommendations to better manage the recharging activity of mobile robots in Section 5.4.

Even though it emerged from our study that the TB was not very efficient in performing tasks, and the long recharging behaviour was not well accepted, the participants still enjoyed using and watching it. The TB made them laugh and gave them something to care about. TB also provided them with a sense of companionship which grew stronger over time, and the TB was a trigger for social interaction between team members. The participants suggested that the robot was perhaps more useful in a social context rather than work, but perhaps that the social part could also be indirectly good for work environment. By focusing on the interests and the needs of the users, we can design robots that can improve their overall work experience so that their work becomes more joyful and interesting. The results from this study may not be statistically significant due to small sample size. But we believe that participants' feedback on recharge issues can be considered in the design process of office robots.

Along with the long recharge activity, the TB also spent 41.10% time during the study at its default position (standing at home position performing idle motions). However, the participants did not seem to report this behaviour negatively. We interpreted that because the TB was not moving nor performing verbal behaviours while recharging this may have influenced the negative perception of the TB. This suggests, mobility and verbal behaviours could have an impact on social acceptance of the robot. For example, a long-term study with a social robot with a similar hardware platform as the TB [58], indicated that, the participants reported feeling closer to the robot embodiment and rated the robot embodiment capable of physical movement as more likeable in comparison to a stationary robot having the same verbal behaviours. This motivated us to specifically investigate the mobility and verbal behaviour of the TB while recharging. We conducted a social study described in the next Chapter 6 to explore a socially acceptable strategy for managing user expectations during robot's recharge behaviour.

Chapter 6

Social Study

6.1 Introduction

In the previous Chapter 5 we described a long-term study in which the robot's immobility while recharging negatively affected the overall interaction experience with the participants. We interpreted that there was a need for a social mitigation strategy to manage user's expectations on service degradation imposed due to immobility during recharge. In this chapter we describe a social study where we explored the use of verbal strategies during recharge behaviour of our robot. This study was carried out firstly, to investigate the perception towards an office robot while performing tasks. Secondly, to find out how the robot's verbal behaviour might influence the social acceptance of the robot while recharging. The work described in this chapter was exclusively conducted within the scope of this thesis. We start with describing our experimental approach and design in Section 6.2. We performed subjective and objective analysis on the data gathered from the participants of this study. We then present the results of our questionnaire analysis in Sections 6.4, 6.5. Results from video analysis are presented in Section 6.6. Followed by discussion in Section 6.8 and conclusion in Section 6.9.

6.2 Experimental Approach

Our approach during this study was to investigate what type of behaviour from the robot can help to manage user expectations while the robot is undergoing a service degradation (immobility). The limitation for the robot in our case was, during recharging the robot could not move around (being fixed to charging station) while performing tasks. It was thereby essential for the robot to demonstrate the ability to make the human aware about its limitation in a socially appropriate manner. In Chapter 2 Section 2.1, we described work on transparency to manage user expectations. Previous work on producing transparency from the robot about its ability, intent and limitations, have shown positive effects on people and improved acceptance of the robot [27, 31, 15, 24, 35]. Transparency can include both verbal and non-verbal behaviour. In our scenario, because the robot was shared in an office environment, we envisaged that verbal transparency would be preferable as the participants in the study might not interact with the robot actively, i.e. they might not look at the robot all the time, but they would be able to hear what the robot is saying. This was also the case in the long-term study described in previous Chapter 5, where the participants were not actively interacting with the robot all the time.

A Wizard-of-Oz (WoZ) study was conducted to explore a socially acceptable strategy for the robot's recharge behaviour. The WoZ technique (introduced by Kelley [188]), as a rapid prototyping method, is a widely used evaluation technique in HCI and in HRI research [189, 190], that can result in testing proof-of-concept. WoZ refers to a person (usually the experimenter, or a confederate) remotely operating a robot, controlling any of a number of things, such as its movement, navigation, speech, gestures, etc [190]. In our WoZ study, the behaviours performed by the robot were the same as those of the autonomous robot during the long-term study described in Chapter 5. We decided to perform a Wizard-of-Oz (WoZ) study as it was not essential that the robot in this study be autonomous and to keep the behaviour produced by the robot consistent. Also the room in which this WoZ study was conducted did not have landmarks on the ceiling which were essential for the robot to have a map of the room in order to autonomously navigate in the room. Also the user presence detection system would have required a computer on the desk where the participants were sent to. In order to keep things straight forward and to collect a focused feedback about the behaviour of the robot we performed a WoZ study. Using an autonomous system would have been cumbersome to deploy for this study.

Our study specifically investigated how people perceive a moving robot versus a stationary robot while performing tasks in two battery conditions, battery normal (mobile) and battery low during recharge (stationary) undergoing a service degradation. We designed the robot behaviour for two conditions; *social*: having greater verbal transparency i.e. more explanatory, polite and apologetic and *neutral*: more direct in verbal communication (less explanatory, polite and apologetic). We aimed to investigate the impact of transparency using verbal strategies on the following research questions:

1. How does mobility influence people's perception of the robot while undergoing a service degradation?

2. What impact can verbal strategies have on social acceptance of the robot while it is undergoing a service degradation like recharging?

The main variables in the robot's behaviour were:

a) Movement: The robot's movement (orientation and proximity to the user) while performing tasks.

b) Speech: Use of verbal strategies (transparency, apology, politeness) while recharging.

The main hypotheses for this experiment were related to perception on service degradation (H1) and the effect of verbal strategies (H2):

- H1: People recognise a regression in service quality when the robot goes to recharge.
- H2: The social robot will be preferred by people and will have a positive influence on peoples' perception of the robot more than the neutral robot while the robot is recharging. We define social and neutral robot as follows:
  - Social robot: Robot used more apologetic, polite (more use of words like *"please"*, *"thank you"*, *"sorry"*) and transparent (more explanatory) verbal utterances.
  - Neutral robot: More direct and neutral verbal utterances, no use of polite and apologetic words.

6.2.1 Experimental Procedure

50 participants were recruited from the University from different departments, comprising 31 males and 19 females, with age groups ranging from 18-24(42%), 24-34(40%), 35-44(16%), 45-55(2%). 78% of the participants had never interacted with a robot when asked *"Do you have experience of using robots, for instance, vacuum-cleaning or lawn-mowing robots?"*. Participants first filled in consent forms for video and audio recordings (refer Appendix A. 3) and then were given an instructions sheet to read before entering the experiment room (refer Appendix A. 3):

"We are researchers working in the lab you are about to enter. There is a robot, the Team Buddy (TB) Alex, an office assistant robot that helps us in the lab. TB cannot hear you but you can talk with Alex using a tablet placed on the body, although using the tablet is optional.

The robot can perform tasks like greeting, passing messages left by other team mates and deliver calls (Please note when you hear the phone ring, this is not a real phone call and you can answer the call using the tablet by pressing Yes/No button)

Bob and Paul are professors at this university who work together in the Lab you are entering. Bob is now on holiday and needs to mark some exams. He has forgotten one in the lab and has asked you to mark that for him."

An exam marking task was chosen for this study because we anticipated that it would be better in terms of ecological validity [104, 191] rather than selecting any random task for the participants to perform in an office environment. So in order to create an office-like environment during the study, the participants were given an exam marking task. The participant enters a room (4.5m × 6m, see Figure 6.2) and were asked to mark an exam paper (an answer key was provided). The wizard could control the robot's movement and speech using a GUI based wizard interface remotely, see Figure 6.1. A web camera placed in the corner of the room which allowed the wizard a full live view of the room.

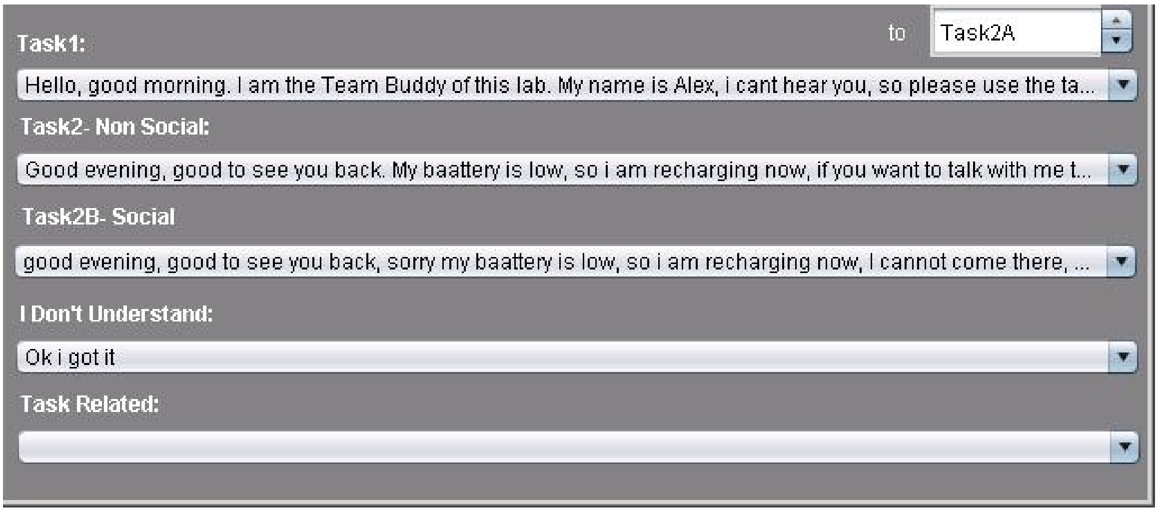


Figure 6.1: WOZ interface

The experiment had two parts, Part A and Part B and both were analysed separately. The first session (Part A) was the same for all 50 participants. This was deliberate to establish a baseline for the experiment where the TB operates normally as it would under normal battery conditions. We envisaged that during long-term interaction it would be usual for people to initially experience the normal functionality of the robot (robot moving around) before they experience regression in its service due to battery limitation (the robot needs to recharge). Hence, during this study we also wanted the participants to first experience the normal functionality of the office robot (i.e. when it can move around). We then investigated if the robot has a limitation how can it affect their acceptance, hence we did not counterbalance the conditions.

However, the participants were not aware initially that the experiment had two sessions. In *Part A* the TB was mobile, refer Figure 6.2. The TB initially greeted them and then performed two tasks, namely message delivery and telephone call delivery after a time interval of approximately 2 minutes in the same order. These tasks were the same from the long-term study reported in Chapter 5. We chose these tasks in order to have some variety, for example greeting is a social task, message delivery is an informative task and telephone call is an urgent utility task. These tasks involved the robot navigating from a default location in the room to the user's desk and then performing a verbal action using an artificial synthesised female voice[1]. The approximate distance the robot would stop from the user was 1.50m, which also corresponds to Hall's social zone [120] (1-3m) for human face to face conversation. Although the robot had expressive capabilities, these were not used as the robot's expressiveness was not the focus of our research.

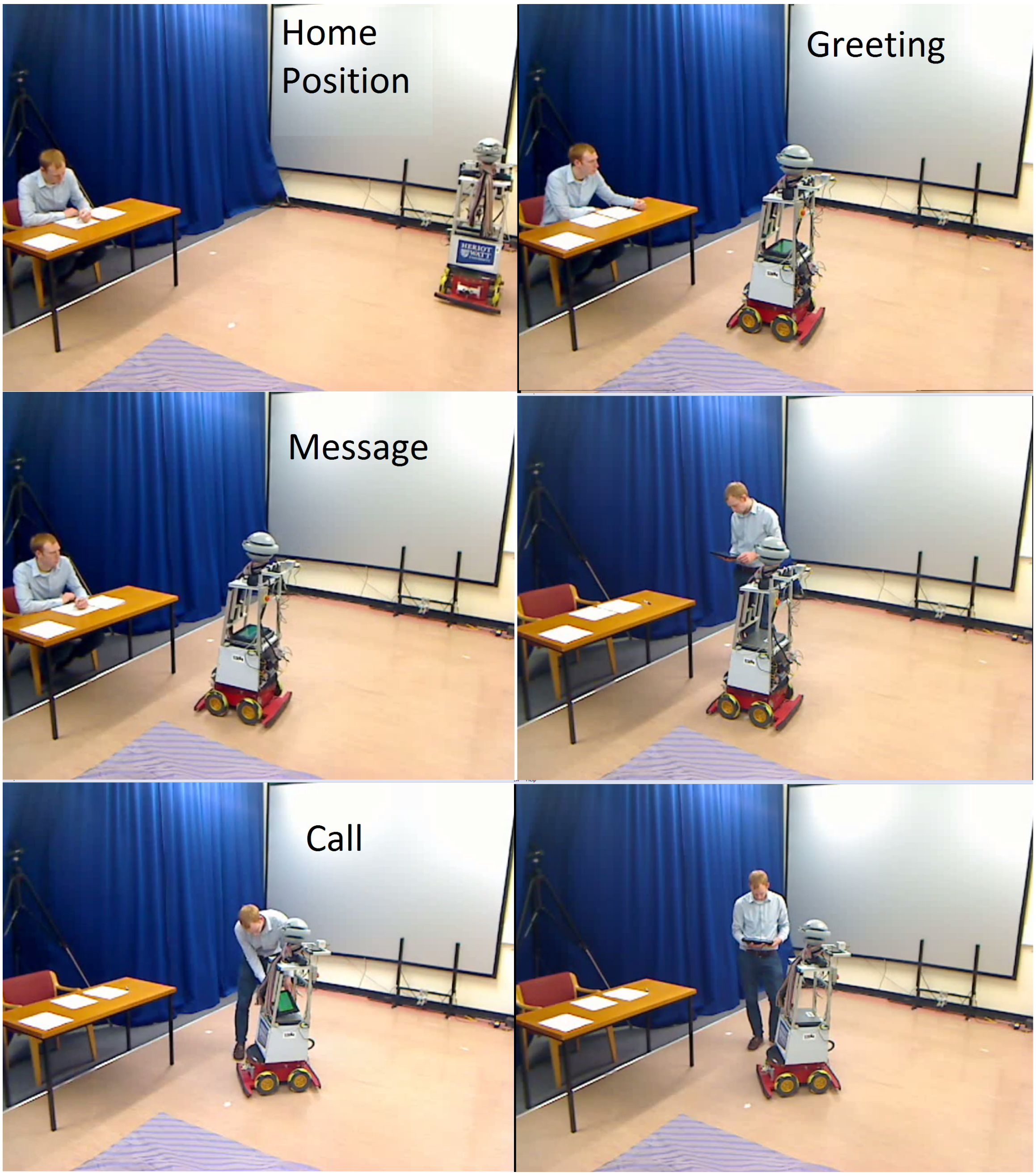


Figure 6.2: Part A- Mobile TB Interaction Example

After marking the exam paper (*Part A* of the experiment), the participant left the

[1]www.cereproc.com

room and answered the first part of the questionnaire. They were then asked to go back to the room, and asked to imagine that some time had passed between the first part of the study (morning time) and now (evening), and mark the second part of the exam paper. In order to simulate the passage of time and the fact that robot's battery may be low after passage of time, we asked the participants to imagine this situation. In *Part B*, the second part of the experiment, the robot performed the same 3 tasks (greeting, message, call) from a recharge position (battery low) in the room. The TB was not facing the user during this session (facing towards the wall/charging station, the same recharge set-up was used as for the long-term experiment, Chapter 5), so there was no face-to-face interaction for *Part B*.

In *Part B* the TB was stationary (docked into the charging station for recharging), refer Figure 6.3. *Part B* had two conditions. In the *neutral* condition, the robot used the same verbal communication as *Part A* for all tasks except for the greeting (refer Table 6.1). In the *social* condition, the robot was apologetic, polite and provided more explanation about its limitation in not being able to move due to recharging activity. There was also more use of words like ***"please", "sorry", "thank you"*** (refer Table 6.2). Previous studies conducted by Bruckenberger et al. [192] and Salem [39] studied the attitude of participants towards their mobile robot. It appears that it is very important for the participants that a robot is able to act politely. The authors suggest from their studies that the robot should be more polite and say words like "please", "thank you" and "sorry". Hence we used similar polite words in our study.

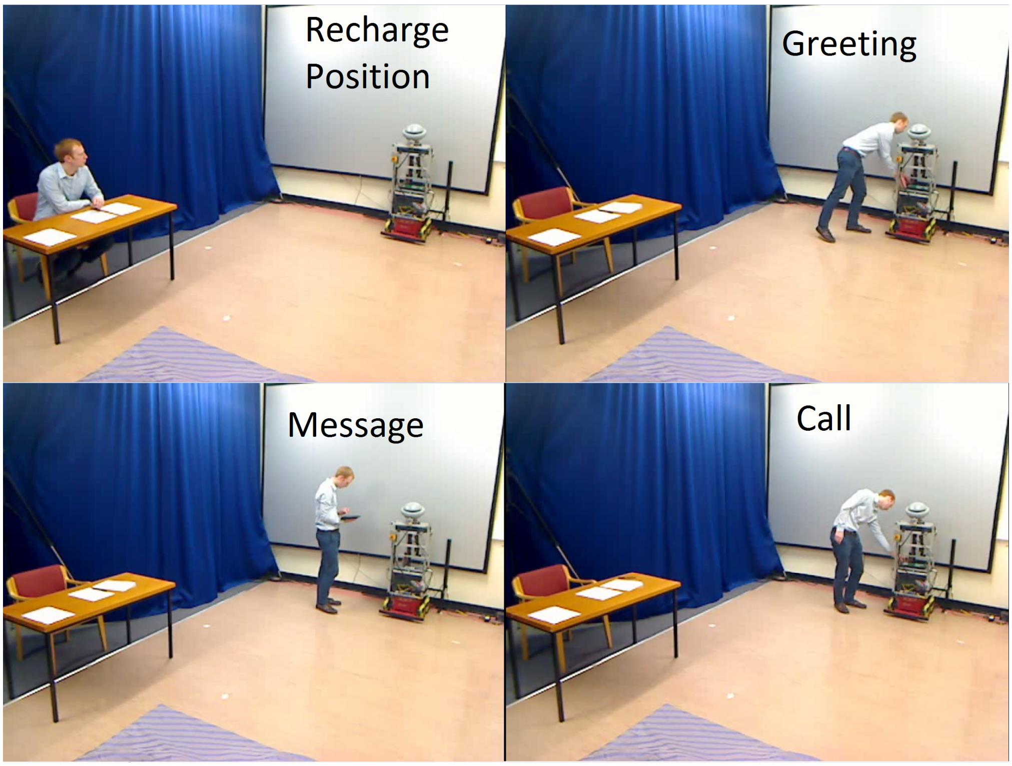


Figure 6.3: Part B- Stationary (recharging) TB Interaction Example

Task	***Part A***	***Part B***
Greeting	Hello, good morning. I am the Team Buddy of this lab. My name is Alex, I cannot hear you, so please use the tablet placed on me, to talk with me, hope you have a good day. My battery is fully charged.	Good evening, good to see you back. My battery is low, so I am recharging now, if you want to talk with me then use the tablet placed on me
Message	There is a message left by Paul. You need to mark the exam Part A, If you want to reply then use the tablet placed on me	There is a message left by Paul. You need to mark the exam Part A, If you want to reply then use the tablet placed on me
Message Reply	I got your message for Paul and will deliver it when I see him	I got your message for Paul and will deliver it when I see him
Phone Call	There is a call for you, use the tablet to answer the call	There is a call for you, use the tablet to answer the call

Table 6.1: Condition 1: Neutral Verbal Utterances

Task	***Part A***	***Part B***
Greeting	Hello, good morning. I am the Team Buddy of this lab. My name is Alex, I cannot hear you, so please use the tablet placed on me, to talk with me, hope you have a good day. My battery is fully charged.	Good evening, good to see you back, **sorry** my battery is low, so I am recharging now, I cannot come there, but if you want to talk with me then **please** use the tablet placed on me
Message	There is a message left by Paul. You need to mark the exam Part A, If you want to reply then use the tablet placed on me	There is a message left by Paul. You also need to mark the exams Part B. **Sorry** I am recharging so I cannot come there, but if you want to reply then **please** use the tablet placed on me
Message Reply	I got your message for Paul and will deliver it when I see him	I got your message for Paul and will deliver it when I see him, **thank you**
Phone Call	There is a call for you, use the tablet to answer the call	There is a call for you. **Sorry** I am recharging, so I can't come there, **please** pick up the tablet placed on me to answer the call

Table 6.2: Condition 2: Social Verbal Utterances

Participants were randomly assigned to one of the two conditions. Thus 25 participants interacted with the *social* robot and 25 of them interacted with the *neutral* robot in *part B*. Figure 6.4 shows the experimental design for the participants and hypothesis for each condition. The total interaction took on average 8 minutes for each session depending on how long it took the participant to mark the exam paper. After the second session(*part B*), the participant was again asked to fill in the questionnaire.

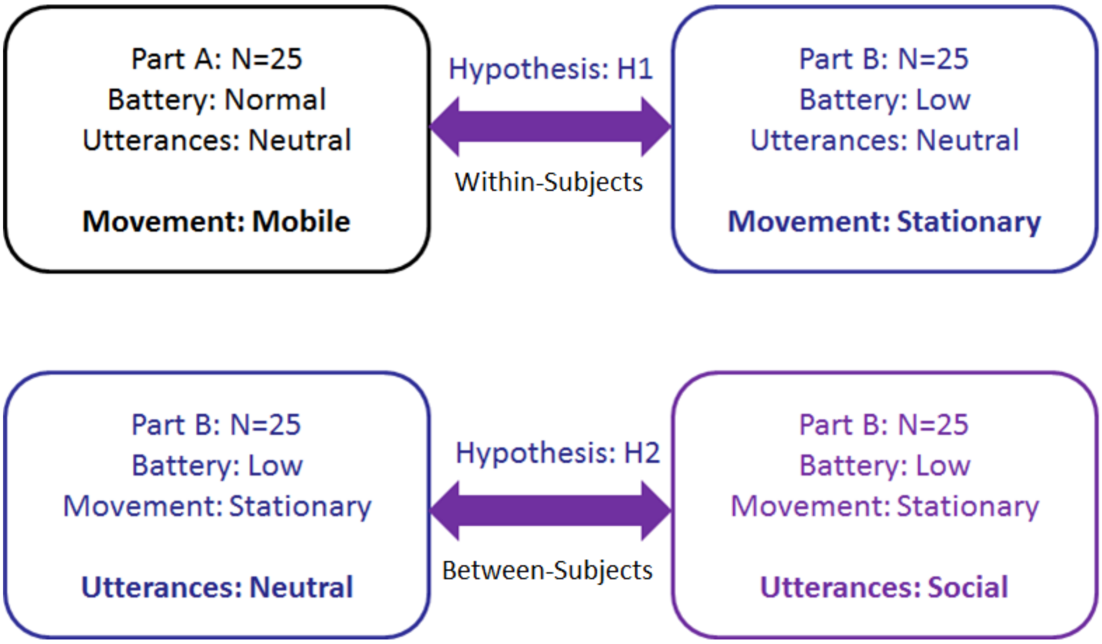


Figure 6.4: Experimental Design

When the participants tried to have a conversation with the robot using the tablet interface placed on the robot, the robot responded by saying *"Sorry my responses are limited, I didn't understand you"*. These responses were deliberately fixed to prevent the participant from having any false sense of intelligence from the robot.

6.3 Questionnaire Analysis

In this section, we describe the analysis performed on the questionnaire data. The TB performed 3 tasks, namely greeting at the start of the interaction, message delivery and finally the call delivery task at the end of the session. The task sequence was the same for all participants. The participants were asked to rate the questions on a 7 point Likert scale, 1:Disagree strongly, 2:Disagree moderately, 3:Disagree a little, 4:Neither agree nor disagree, 5:Agree a little, 6:Agree moderately, 7: Agree strongly. The participants rated the interaction twice (Pre-Post) after each interaction *Part A* (mobile TB) and *part B* (stationary/re-charging TB). The questionnaire was piloted with 3 test participants and refinements were made to the questionnaires following their feedback. The questionnaire is described in Appendix A, Section A. 3. These questionnaires were used in previous studies in the LIREC project [171, 193, 194].

The items on the questionnaire were mainly designed to investigate how participants perceived the interaction in the context of its service and verbal communications. The questionnaire analysis was performed on factors such as, the task context-investigating the utility of the robot; and social presence related to the feeling of being in the company of someone: "the perceptual illusion of non mediation" [195]. The concept about social presence has been previously used to measure people's responses towards different technological artefacts, such as virtual reality environments [196], text-to-speech voices [197], and social robots [198, 199].

We chose these as our primary factors for investigation as the results from our long-term study (Chapter 5) pointed out that the limitations during robot's recharge (when the robot was immobile and not performing any verbal behaviour) were not well accepted by the participants of the study. So we specifically wanted to investigate the tasks, social and social presence aspect of the robot during interactions in this study. We also anticipated that these three factors (tasks, social and social presence) will allow us to investigate the effects of service degradation *H1* and influence of verbal utterances *H2* (the hypotheses proposed for this study, Section 6.2).

The results in this section are divided two main parts, linked to the hypotheses for our study (service degradation and verbal utterances). First we report the results from the mobile vs stationary case which relates to our hypothesis H1 (influence of service degradation); then the stationary robot which relates to our hypothesis H2 (influence of verbal utterances). For all the graphs reported in this section, Y-axis on the graphs describes the mean ratings given by the participants. All graphs have Error bars which represent (+/-) 1 SE (Standard Error) and reliability measure, Cronbach alpha: α. Table 6.3 provides an overview of the statistical tests and relevant sections where results are reported.

Factor	**Mobile Vs Stationary**	**Social Vs Neutral**
Tests, Hypothesis	**Within-Subjects, H1**	**Between-Subjects, H2**
Task	Section 6.4.1	Section 6.5.1
Social Presence	Section 6.4.3	Section 6.5.2

Table 6.3: Statistical Analysis Overview

6.4 Mobile Vs Stationary Robot

The results in this section investigates our hypothesis, *H1: People recognise a regression in service quality when the robot goes to recharge.* In this section we report on the mobile (N=25) Vs stationary case (N=25) for neutral condition, within-subjects comparison. The verbal utterances used by the robot in all 3 tasks were exactly the same for both conditions (mobile and stationary), this allowed us to investigate the influence of mobility specifically.

6.4.1 Task Context: Mobile Vs Stationary

We conducted a factorial ANOVA[2] for the task scale and t-tests for social and social presence questionnaire items. Using mean ratings given to the robot as the dependent variable and tasks (greeting, message and call) as the independent variable. Participants ratings were subjected to a 2 × 3 analysis of variance having two levels of mobility (mobile, stationary) and three levels of tasks (greeting, message and call). All effects were statistically significant at the .05 significance level. The results of 2 × 3 Factorial ANOVA are as follows. Table 6.4 summarises the results for the 3 tasks, describing the question asked to the participant, condition (mobile/stationary), Mean, Standard deviation (SD), Standard error mean (SE) and p-value. Figure 6.5, shows the mean ratings during each task (greeting, message, call) in the mobile Vs stationary robot conditions.

Question	Condition	Mean	SD	SE	p
I liked it when the TB greeted me	Mobile	5.64	1.524	.305	1.000
	Stationary	5.64	1.114	.223	
I liked it when the TB delivered the message to me	Mobile	5.88	1.130	.226	.015
	Stationary	4.96	1.428	.286	
I liked it when the TB delivered the call to me	Mobile	5.56	1.325	.265	.047
	Stationary	4.76	1.451	.290	

Table 6.4: Task Context: Mobile Vs Stationary Results

There was no significant main effect[3] for task type (greeting, message, call), $F(2,96) = 3.057, \rho = .052, \eta_p^2 = .060$. This implies that there was no difference in how participants rated the robot for each task. There was a significant interaction between task and condition (mobile, stationary) $F(2,96) = 3.312, \rho = .041, \eta_p^2 = .065$. This suggests that there was a significant difference between conditions (mobile and stationary) for each of the task.

[2]Factorial ANOVA measures whether a combination of independent variables predict the value of a dependent variable.

[3]The main effect indicates there are differences among means for these items.

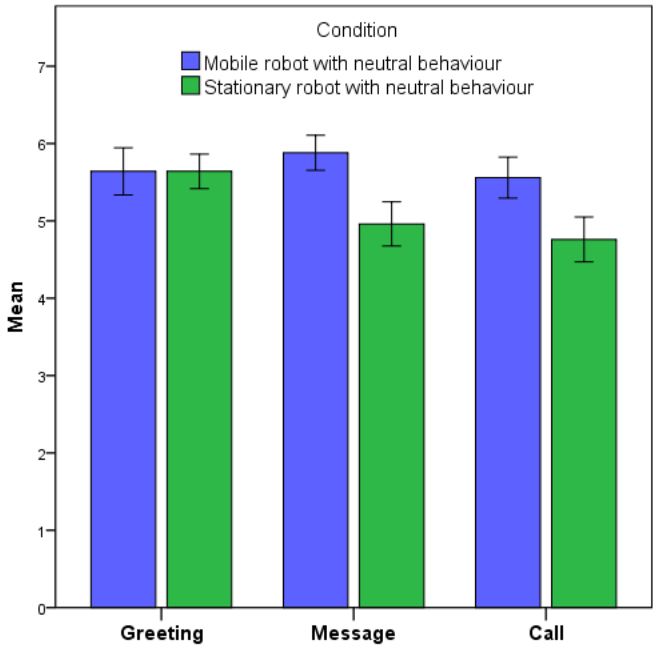


Figure 6.5: Task context graph, N=25, $\alpha = 0.81$

To further investigate where exactly differences were, we look at the simple effect[4], there was a significant difference in ratings for message task between the mobile and stationary condition, Mobile robot: $M = 5.88, SE = .22$; Stationary robot: $M = 4.96, SE = .28, \rho = .015$. This shows the participants rated the mobile robot significantly higher than the stationary robot for message delivery task.

There was a significant difference between ratings for call task between the mobile and stationary condition Mobile robot: $M = 5.56, SE = .26$; Stationary robot: $M = 4.76, SE = .29, \rho = .047$. Which indicates the participants rated the mobile robot significantly higher than the stationary robot for call delivery task.

However, there were no significant differences for the greeting task between the mobile and stationary condition, Mobile robot: $M = 5.64, SE = .30$; Stationary robot: $M = 5.64, SE = .22, \rho = 1.000$. In fact the mean ratings for greeting task for both mobile and stationary conditions were exactly the same.

There was a significant difference between ratings for usefulness between the mobile and stationary condition, when asked the question *"The TB was useful"*. Mobile ($M = 5.60, SE = .21$), stationary ($M = 4.60, SE = .20$), $t(24) = 4.201, \rho = .000$. This may be due to the fact the the mobile robot could physically approach the participants while performing tasks, while in the stationary condition the participants sometimes had to go towards the robot to receive the message and call.

These result suggests that for a social task like greeting, the participants did not rate the mobile robot higher than stationary robot (the result from greet task does

[4]Simple effect is the effect of one independent variable within one level of a second independent variable.

not support hypothesis *H1*). However for both utility tasks like the message delivery and call delivery task the participants rated the mobile robot significantly higher than stationary robot supporting our hypothesis *H1* in these two tasks. This suggests that the participants expected more from the robot in terms of its service when it comes to utility based tasks.

6.4.2 Influence of Tasks: Mobile Robot

Considering the previous results from the mobile vs. stationary condition (Section 6.4.1) on tasks, we wanted to investigate further if the type of task (greeting, message, call) influenced participants rating of the robot. In this section we report mobile robot questionnaire data for Part A only which was the baseline for this study (total N=50).

A one-way within subjects (or repeated measures) 1 (Condition: Mobile) $\times$ 3 (Tasks: Greeting, message, call) ANOVA was conducted to compare the effect of tasks type (greeting, message, call) on the mean ratings provided by the participants. There was a significant effect of task type, $Wilks'Lambda = 0.856, F(2, 48) = 4.039, \rho = .024$. Three paired samples t-tests were used to make post hoc comparisons between conditions (tasks)[5]. A first paired samples t-test indicated that there was a significant difference in the ratings for message delivery task ($M = 5.86, SD = 1.143, SE = .162$) and call task ($M = 5.52, SD = 1.282, SE = .181), t(49) = 2.75, \rho = .008$. However, there was no significant difference between the greeting ($M = 5.90, SD = 1.282, SE = .181$) and call tasks ($M = 5.52, SD = 1.282, SE = .181), t(49) = 2.05, \rho = .045$. A third paired samples t-test indicated that there was no significant difference greeting ($M = 5.90, SD = 1.282, SE = .181$) and message task ($M = 5.86, SD = 1.143, SE = .162), t(49) = 0.244, \rho = .808$.

These results suggest that task type had an effect on user's ratings. Our results indicate, that users rated the robot's service on the message and greet task higher than the call task. The difference between greeting and message/call task was not significant, however greeting was rated higher than both message and call tasks. This indicates that users liked the robot's social task (greeting) more in comparison to utility tasks like message or call delivery. The difference was significant between message (mean higher) and call task, both these tasks were utility based tasks, but during an urgent task like call delivery the users rated the robot significantly lower than in the message delivery task. We interpret that this result (call task rated lower) may be due to the fact that participants perceived that the robot took longer to bring the phone to user. This result also echoes from the long-term experiment, where users complained about the slow speed of the robot during call task (Chapter 5 Section 5.3.5), even though the navigation speed of the robot was same for all tasks.

[5] Instead of using the value 0.05 we used the value 0.017 as the cut off as we are conducting 3 tests, so .05 divided by 3 = 0.017.

We suppose that navigation speed of the robot could be task specific and the users expect a higher navigation speed for the robot performing an urgent task like call delivery.

6.4.3 Social Presence: Mobile Vs Stationary

A paired-samples t-test was conducted to compare the mean ratings on social presence in each mobile and stationary conditions. Table 6.5 summarises the results for social presence, describing the question asked to the participant, condition (mobile/stationary), Mean, Standard deviation (SD), Standard error mean (SE) and p-value. Figure 6.6, shows the mean ratings for social presence scale in the mobile Vs stationary robot conditions.

Question	Condition	Mean	SD	SE	t(24)	p
I noticed the TB	Mobile	6.44	.651	.130	2.089	.047
	Stationary	6.04	.841	.168		
The TB noticed me	Mobile	5.84	1.248	.250	3.302	.003
	Stationary	5.16	1.748	.350		
The TB Presence was obvious to me	Mobile	6.04	1.060	.212	3.894	.001
	Stationary	5.16	1.491	.298		
My Presence was obvious to the TB	Mobile	5.56	1.781	.356	.756	.457
	Stationary	5.24	1.363	.273		

Table 6.5: Social Presence: Mobile Vs Stationary Results

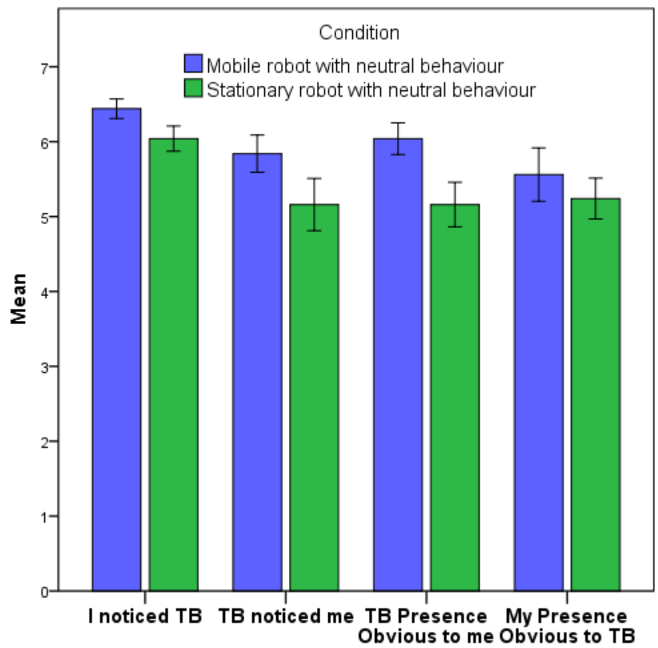


Figure 6.6: Social Presence graph, N=25, $\alpha = 0.78$

There was a significant difference between ratings for *"I noticed the TB"* between the mobile and stationary condition. Mobile ($M = 6.44, SE = .13$), stationary ($M = 6.04, SE = .16$), $t(24) = 2.089, \rho = .047$. There was also significant difference for *"The TB noticed me"*. Mobile: ($M = 5.84, SE = .25$), stationary ($M = 5.16, SE = .35$), $t(24) = 3.302, \rho = .003$. This suggests that the participants perceived that the TB is noticing them and vice-versa more in the mobile condition than in the stationary condition (supporting our hypothesis *H1*). This result also may be due to the fact the the mobile robot was approaching them while performing tasks thus influencing the participants perception.

For presence, there was a significant difference between ratings for *"The TB Presence was obvious to me"*, Mobile ($M = 6.04, SE = .21$), stationary ($M = 5.16, SE = .35$), $t(24) = 3.894, \rho = .001$ (supporting our hypothesis *H1*). However for *"My Presence was obvious to the TB"*, Mobile ($M = 5.56, SE = .35$) and stationary ($M = 5.24, SE = .27$), $t(24) = .756, \rho = .457$ the difference was not significant. This indicates that the participants perceived that the TB is not noticing their presence as much as they are noticing the TB when the TB was mobile.

However, there was a significant difference in the ratings for companionship, when asked the question *"I felt in the company of TB"*, Mobile robot ($M = 5.16, SE = .28$) and stationary robot ($M = 3.88, SE = .34$), $F(1, 48) = 8.19, t(24) = 3.059, \rho = .005$. So the participants felt more in the company of the robot when the robot was mobile.

There was also significant difference between ratings for politeness, when asked the question *"The TB was polite"*, between the mobile and stationary condition. Mobile ($M = 6.32, SE = .15$), stationary ($M = 5.88, SE = .21$), $t(24) = 2.201, \rho = .031$. This results suggest that the participants found the robot to be more polite when it was mobile. This was an unanticipated result as as the verbal utterances for both mobile and stationary robot were neutral and exactly the same. However, it also suggests that people recognised a regression in service quality when the robot went to recharge.

Summary: Mobile Vs Stationary Robot Questionnaire Results

1. **Task Context:** Significant differences were found between the mobile and stationary cases for message and call delivery tasks in the neutral condition. So it appears that the regression in service quality was recognised by participants as the stationary robot was rated much lower than the mobile robot in all cases except for the greeting task and supports our hypothesis *H1*. It appears that for non-social or utility based tasks, mobility seems important and user's preference for mobility may depend on the type of task. Also there was a significant difference between the mobile and stationary conditions for usefulness of the robot supporting our hypothesis *H1* for usefulness.

2. **Social Presence:** There was a significant difference between mobile and stationary condition for all questions in social presence scale except for *"My Presence was obvious to the TB"*. Suggesting that the participants perceived that the TB is noticing them more in mobile condition than stationary condition supporting our hypothesis *H1*. However, hypothesis *H1* was not supported for *"My Presence was obvious to the TB"*. However there was a significant difference between mobile and stationary condition in terms of companionship and politeness, supporting hypothesis *H1*.

The results in this section were also cross verified by using non-parametric tests, Wilcoxon signed rank test (Appendix A, Section A. 7, Table A.2).

6.5 Social Vs Neutral

The results in this section investigate our hypothesis, *H2: The social robot will be preferred by people and will have a positive influence on peoples' perception of the robot more than the neutral robot while the robot is recharging.* We report only on the stationary robot (recharging) Part B, for the social condition (N=25) vs neutral condition (N=25), between groups comparison in this section.

6.5.1 Task Context: Social Vs Neutral

Using mean ratings given to the robot as the dependent variable and tasks (greeting, message and call) as the independent variable, participants ratings were subjected to a 2×3 analysis of variance having two levels for verbal utterances (social, neutral) and three levels of tasks (greeting, message and call). The results of the factorial ANOVA are as follows. Table 6.6 summarises the results for the 3 tasks, describing the question asked to the participant, condition (social, neutral), Mean, Standard deviation (SD), Standard error mean (SE) and p-value. Figure 6.7, shows the mean ratings during each task (greeting, message, call) in the stationary robot condition.

Question	Condition	Mean	SD	SE	p
I liked it when the TB greeted me	Social	5.92	1.038	.208	.362
	Neutral	5.64	1.114	.223	
I liked it when the TB delivered the message to me	Social	5.36	1.655	.331	.365
	Neutral	4.96	1.428	.286	
I liked it when TB delivered the call to me	Social	4.88	1.878	.376	.802
	Neutral	4.76	1.451	.290	

Table 6.6: Task Context: Social Vs Neutral Results

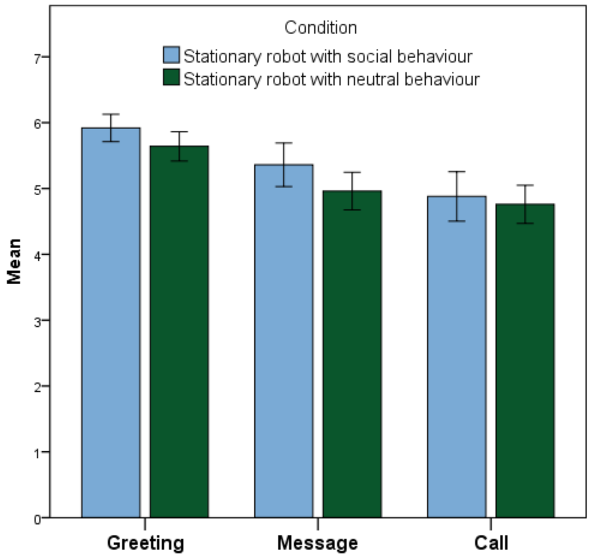


Figure 6.7: Task context graph, N=25, $\alpha = 0.78$

There was a significant main effect for task type (greeting, message, call) in the stationary robot condition, $F(2, 96) = 12.28, \rho = .000, \eta_p^2 = .204$. This implies that there was a significant difference in the ratings the participants gave to the robot during the stationary robot behaviour for each task. Post hoc analysis revealed that there was a significant difference between the greet $(M = 5.78, SE = .15)$ and message task $(M = 5.15, SE = .21), \rho = .019$. There was also a significant difference between greeting $(M = 5.78, SE = .15)$ and call $(M = 4.82, SE = .23), \rho = .000$. The greeting task was rated significantly higher than the call and message task.

There was also a significant difference between call $(M = 4.82, SE = .23)$ and message tasks $(M = 5.15, SE = .21), \rho = .024$. The message delivery task was rated significantly higher than call delivery task. This indicates that the participants rated each task differently indicating that the type of task influenced user's perception when the robot is stationary (recharging) irrespective of the fact whether the robot was using social or neutral verbal utterances. The results suggest, the call delivery task was rated significantly lower than both greeting and message delivery task. This indicates that for an urgent utility task like call delivery, the participants expected better service from the TB. There were no significant differences for condition (social and neutral) $F(1, 48) = .601, \rho = .44, \eta_p^2 = .012$, suggesting the social verbal utterances did not influence the ratings of the users on task scale.

There was no significant difference for usefulness, when asked the question *"The TB was useful"*. Social: $M = 5.16, SE = .33$, Neutral: $M = 4.60, SE = .22$, $t(48) = 1.405, \rho = .167$. However, the mean ratings for all tasks were higher for social condition than neutral condition. Overall, the mean ratings were higher for the social condition were higher than neutral condition for task context and usefulness of TB.

6.5.2 Social Presence: Social Vs Neutral

An independent-samples t-test was conducted to compare the mean ratings given to the robot on social presence in social and neutral conditions. Table 6.7 summarises the results for the social presence, describing the question asked to the participant, condition (social, neutral), Mean, Standard deviation (SD), Standard error mean (SE) and p-value. Figure 6.8 shows the mean ratings from the questionnaires for the social presence of the robot in the stationary robot condition.

Question	Condition	Mean	SD	SE	t(48)	p
I noticed the TB	Social	5.84	1.281	.256	-.653	.517
	Neutral	6.04	.841	.168		
The TB noticed me	Social	3.88	1.922	.384	-2.463	.017
	Neutral	5.16	1.748	.350		
The TB Presence was obvious to me	Social	5.28	1.595	.319	.275	.785
	Neutral	5.16	1.491	.298		
My Presence was obvious to the TB	Social	4.68	1.887	.377	-1.203	.235
	Neutral	5.24	1.363	.273		

Table 6.7: Social Presence: Social Vs Neutral Results

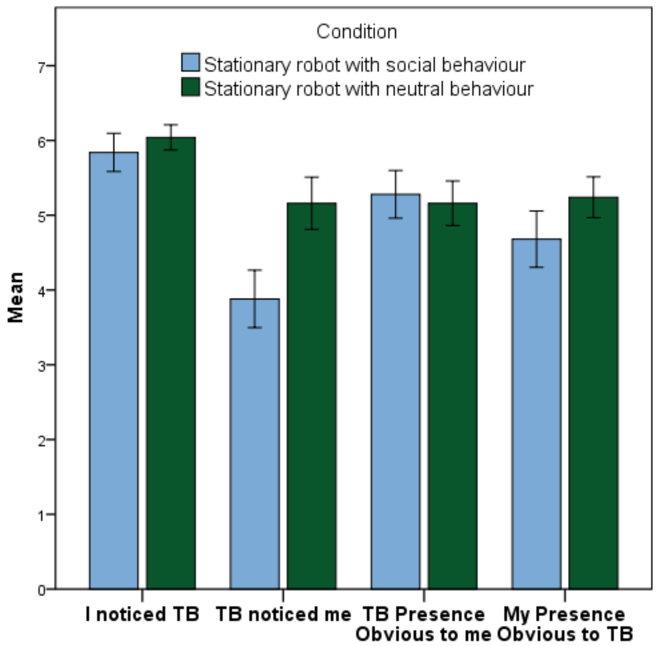


Figure 6.8: Social presence graph, N=25, $\alpha = 0.71$

There was no significant difference in the ratings for *"I noticed the TB"*, Social:$M = 5.84, SE = .25$, Neutral: $M = 6.04, SE = .16$, $t(48) = -.653, \rho = .517$. In fact the mean ratings for the neutral condition was slightly higher than for the social condition. However, there was a significant difference in the ratings for *"The TB noticed me"*, Social:$M = 3.88, SE = .38$, Neutral: $M = 5.16, SE = .35$, $t(48) = -2.463, \rho = .017$. The mean rating for neutral condition was significantly higher than for the social condition. This was an unanticipated result as this suggests that the participant perceived the robot with neutral utterances noticing them more and vice-versa. This result indicates contradiction to our hypothesis *H2*.

Also the results for *"TB Presence was obvious to me"* was not significant between the conditions. In fact the mean rating for *"My Presence was obvious to the TB"* was higher for neutral condition ($M = 5.24, SE = .27$) than social condition ($M = 4.68, SE = .37$), $t(48) = -1.203, \rho = .235$.

However, there was a significant difference in the ratings for Companionship, when asked the question *"I felt in the company of TB"* , Social:$M = 4.84, SE = .32$, Neutral: $M = 3.88, SE = .34$, $t(48) = 2.016, \rho = .049$. These results suggests that social verbal utterances (polite, apologetic, more transparent) from the robot provided the feeling of companionship. This result supports hypothesis *H2* for companionship. The difference was not significant for politeness of the robot, when asked the question *"The TB was polite"*, although the rating for social ($M = 6.32, SE = .15$) robot was higher than neutral ($M = 5.88, SE = .21$), $t(48) = 1.661, \rho = .103$.

The results from social presence questionnaire suggests that the social verbal utterances from the robot did not have an influence on participants ratings on the robot in terms of its social presence. Hypothesis *H2* was contradicted in this case. Also the mean ratings were higher for the neutral condition for all questions except for the *"TB Presence was obvious to me"*. This might be due to the fact that the use of social verbal utterances (polite, apologetic, more explanatory) made the participants more aware of the limitations of the robot when the robot used social verbal utterances.

Summary: Social Vs Neutral Questionnaire Results

1. **Task Context:** Significant differences were found between conditions (social vs neutral) for each task. However, no significant differences were found between social and neutral conditions on task scale and usefulness of the robot. Suggesting that social verbal utterances did not influence participants ratings.

2. **Social Presence:** For social presence there was no significant difference between social and neutral conditions. So hypothesis *H2*, was contradicted on the social presence scale. However, there was a significant difference between conditions (social vs neutral) for companionship, so social utterances had a positive influence, supporting hypothesis *H2* for companionship.

The results in this section were also cross verified by using non-parametric tests Mann-Whitney test (Appendix A, Section A. 8, Table A.3).

6.5.3 Open Questions

At the end of the questionnaire (after finishing both parts of the experiment) participants were specifically asked *"Which team buddy would you prefer Part A-mobile or Part B-stationary?"*, 64% (N=32) preferred *Part A-mobile*, 20% preferred *Part B-stationary* (N=10) and 16% had no preference (N=8). So most (64%) participants preferred the mobile robot more than the stationary robot. Out of the 32 who preferred *Part A-mobile*, 15 (60% out of 25 participants for *neutral*) had interacted with the *neutral* robot and 17 (68% out of 25 participants for the *social*) with the *social* robot. Hypothesis *H1* was supported in this case, however, there was no significant difference in condition (social and neutral) on the preference for Part A/B. For participants who preferred *Part B-stationary*, there were 5 from each condition (20%) and from participants who preferred both versions 5 (20%) had interacted with the *neutral* and 3 with the *social* robot (12%).

We also asked the participants open questions about their preference for Part A/B, the best and worst aspect for Part A/B. the following questions were asked to the participants.

- *"Why did you prefer Part A/B or Both Team buddy? can you provide a reason?".*
- *"What was the worst aspect of the Teambuddy?"*
- *"What was the best aspect of the Teambuddy?"*

We annotated and categorised their responses into comments related to social aspects, verbal, utility and mobility. We chose these categorises specifically as we wanted to analyse their responses relating to social perception, interaction, verbal, utility and mobility aspect of the TB. We had 2 annotators who categorised these responses, the inter-annotator agreement was found to be 91% overall for 100 responses. We summarise important findings looking at the feedback received from the participants as follows (Detailed responses are reported in Appendix A. 6).

Part A- Mobile: Why did you prefer Part A/B, reason: The participants who preferred Part A indicated from their answers that the fact that the robot could move during Part A made them prefer the mobile robot more than stationary robot. We categorised their responses by reasons they provided. A total 32 participants answered they preferred the mobile robot, out of which 28 indicated that mobility was influencing factor, 17 reasons indicated that the social aspect was influential. Some examples of reasons provided by participants are described below (Detailed responses are described in Appendix A, Section A.6 Subsection P):

- *"Especially the part where it approached me and introduced himself, was nice; in the second part the robot was standing still at a distance."* [P3]
- *"Part A as it felt more interactive while team buddy faced me, indicating that it knows where i was"*[P15]
- *"I preferred part A because TB was able to interact with me and moving towards me better than in part B."* [P20]
- *"Because by moving TB make my life easier, and should actually move even closer to me to bring the tablet to my desk. TB part B was kind of useless and more disruptive especially if we are considering the end of a tiring busy day."*[P27]

Part B- Stationary: Why did you prefer Part A/B, reason: The participants who preferred Part B- stationary robot, indicated the social aspect was influential for them preferring the stationary robot. (Responses: N=10, mobility:6, social:4). Perhaps the participants found the TB to be disruptive while it was moving and watching them made them uncomfortable.

- *"I liked knowing where the Team Buddy was and I didn't feel as though it was watching me."* [P33]
- *"I liked part B as the team buddy goes silent while it's charging."* [P36]
- *"movement of robot made me uncomfortable and did not like the face, as robot didn't move or face me in part B it was much better."* [P42]

Both- Mobile/Stationary: Why did you prefer Part A/B, reason: The participants who preferred both parts, stated social reasons (N=8, n/a:4, social:4). It appears that as the interaction capabilities of TB were same for both parts, 8 participants did not seem in favour any condition (mobile/stationary) more than the other.

- *"It was the same thing - just interacting in different circumstances (charged/not charged). The behaviour was appropriate in both contexts."* [P48]
- *"part A was efficient but very clinical. Part B was exposing a 'disability'. I liked them both but I think I would also like it if I could converse more with it."* [P50]

Irrespective of whether the participants interacted with a social or a neutral robot, regression in service quality was not accepted by the participants, supporting our hypothesis *H1*.

Neutral Condition- Part B: What was the best aspect of the Teambuddy? In the neutral condition (N=25), 11 participants directly indicated that the verbal behaviour of the robot in terms of transparency (providing explanation) for not able to move to perform tasks was the best aspect. 6 participants indicated that the TB could still perform tasks while recharging was the best aspect. (Detailed responses described in Appendix A, Section A.6 Subsection N)

- *"verbal notifications."* [N1]
- *"explaining about having to recharge."*[N3]
- *"Very clear about its limitations."*
- *"He's still capable with the easy tasks even when he's charging."*[N10]
- *"Informed me that it was recharging just after he noticed me, performed every task however it could not move."* [N22]
- *"Cordial attitude and telling me why that because it was recharging it would not move."*[N19]

Neutral Condition- Part B: What was the worst aspect of the Teambuddy? 7 participants indicated the TB was not moving around while recharging was the worst aspect and 3 participants indicated that the fact that TB was not facing them while recharging them was the worst aspect.

- *"Didn't face me, was quite far from me."*[N5]
- *"I felt a bit neglected. He could've been more interactive even without moving."*[N6]
- *"Not being able to move while recharging."*[N17]
- *"It didn't move, so I had to stand up to perform the tasks, I felt this was disruptive and I had to put effort in it."*[N22]
- *"That while charging, team buddy faced away from me. would be better to if it was able to recharge at a slight angle to the office space, so not to imply its 'ignoring you."*[N25]

Social Condition- Part B: What was the best aspect of the Teambuddy? However, in the social condition (N=25), the verbal behaviour of the robot (transparency, politeness, apology) was indicated as the best aspect by 12 participants while it was recharging. Also 4 participants indicated that the TB could still perform tasks while recharging was the best aspect. (Detailed responses in Appendix A, Section A.6 Subsection S)

- *"The apology."*[S2]
- *"It was polite."* [S7]
- *"I liked the way it greeted me when I came in and told me it was recharging."* [S18]
- *"Being able to tell me why it wasn't able to move towards me."* [S]
- *"Announced it would unable to move towards me."* [S10]
- *"friendly tone of voice."* [S24]

In social condition participants specifically indicated that the verbal behaviour of robot was the best aspect, especially quoting politeness and the apology by the TB as the best aspect. This indicates that in the social condition the use of verbal strategies (politeness, apology, explanation about limitations of robot) was noticed by the participants more than in the neutral condition (supporting hypothesis *H2*). In both social and neutral conditions, in total 10 participants (Social: 4, Neutral:6) answered that, the TB could still perform tasks while recharging was the best aspect. So it appears that the TB managing to perform verbal tasks while recharging caused a positive impact on the participants perception.

Social Condition- Part B: What was the worst aspect of the Teambuddy? 10 participants indicated the TB not moving around while recharging was the worst aspect and 5 participants indicated that the fact that TB was not facing while recharging them was the worst aspect.

- *"It cannot move while recharging."* [S3]
- *"It was facing away from me - less personal."* [S6]
- *"not facing me or move."* [S9]
- *"Feels more disruptive if you have to go over it. No advantage taking the call yourself."* [S16]

- *"TB could not move which make the effort to move to TB more annoying especially while you are working. There is a sort of submission of human to robot, if I have to move to the robot. I did not like it because it actually make my life more complicated than easier."* [S17]

In terms of the worst aspect of the TB, the immobility of the TB while recharging (mentioned 17 times, Neutral:7, Social:10) caused the participants to dislike this aspect of the TB. Also the fact that the TB did not face the participants while recharging also did not seem to impress the participants (mentioned 8 times, Neutral:3, Social:5).

Other Findings

If you have any comments, add them here: Part B- Recharging: We also asked the participants for other comments they wanted to mention in the questionnaire. Some comments are described below (Detailed responses in Appendix A, Section A.6 Subsection A).

- *"Moving while performing a task is quite important as it maximises the experience. In an office environment where the employee can not stand up and move you expect the robot to do it should be move while charging."* [A47]
- *"May be TB should be on off mode while recharging instead of half-available which would avoid negative feelings."* [A17]
- *"It could face other way while charging so it feels more human like."* [A22]

We asked the participant a question about *"I did not like the fact that TB was not facing me"*, the mean rating was 4.22 (N=50, inclining towards Neither agree nor disagree) and no significant difference between the neutral ($M = 4.04, N = 25$) and social ($M = 4.40, N = 25$) condition.

Although, the feedback received from participants from open questions in the stationary/recharging condition, the fact that the TB was not facing them appears to have negative impact on some of the participants perception of the robot. However during recharging the TB did not make idle movements with its head, this also might have influenced the perception of participants and caused a disconnect from the participants.

Other Questions: Participants were asked to rate the questions on a scale of importance (1: Unimportant, 2: Of Little Importance, 3: Moderately Importance, 4: Important, 5: Very Important) their perception about the recharge behaviour of robots in general.

Q1 : Robots should take care of recharging themselves.

Q2 : Robots should be able to communicate about their limitations/failure.

Q3 : Robots should move while performing tasks.

Q4 : Robots should choose their recharge time wisely.

Q5 : Robots should be able to perform communicative (verbal) tasks even when they are recharging.

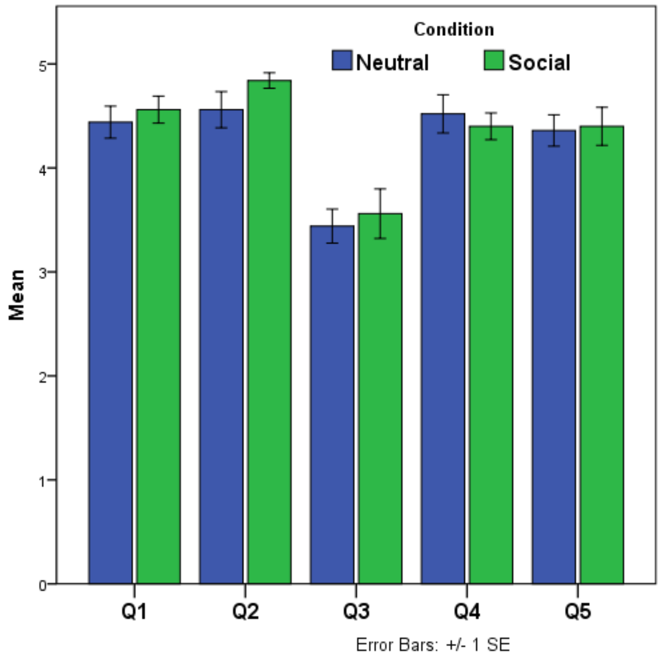


Figure 6.9: Open questions graph, N=50, $\alpha = 0.82$

The results showed (Figure 6.9, the bars on the graph indicate the mean ratings with). There were significant differences in the mean ratings between the *neutral* and the *social* conditions for Q2 ($\rho = .006$) and Q3 ($\rho = .030$). Mean score for Social condition was significantly higher then Neutral condition. Also, participants rated questions 1, 2, 4 and 5 between Very Important to Important indicating that robots should take care of their recharge behaviour wisely and should be able to communicate their limitations (supporting hypothesis *H2*).

Participants rated question 3-"Robots should move while performing tasks" between Important to Moderately Important. Question 5-"Robots should be able to perform communicative (verbal) tasks even when they are recharging" between Very Important to Important suggesting that if the robot is able to perform verbal tasks even while recharging then mobility may not be that important for some tasks. This finding is also consistent with the open questions feedback received from the participants when they answered the TB could still perform tasks while recharging as the best aspect.

6.5.4 Summary of Questionnaire Analysis

We report the main findings from the questionnaire analysis reported in this section:

1. **Mobile Vs Stationary Robot:** The mobile robot was accepted better by participants on the task, usefulness, social presence scale, Companionship and Politeness (hypothesis *H1* was supported). Also it appears that the type of task (no difference in ratings for greeting task) can influence the participants perception of the robot depending whether the robot is mobile or stationary (Section 6.4.1).

2. **Social Vs Neutral Robot:** No significant differences were found for the social robot on tasks, usefulness, social presence, and politeness, suggesting the use of social verbal strategies did not have an influence on the participants ratings (hypothesis *H2* was not supported). However for companionship there was influence of social verbal strategies (Section 6.5).

3. **Open Questions:** 64% of participants preferred the mobile robot again suggesting that regression in service quality was not preferred by the users (hypothesis *H1* was supported). Also verbal transparency about the robot's limitation/failures and during recharge appears to be important for users (Section 6.5.3). The feedback on open questions also showed that mobility was preferred by the participants and verbal transparency positively influenced participants perception during recharge (hypothesis *H2* was supported). Although the participants who liked Part A more than Part B did not seem to like the fact that the TB did not face them during recharging.

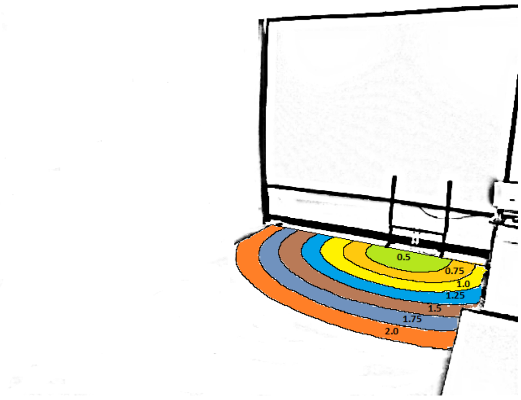
6.6 Video Analysis

The aim of performing video analysis in this study was to perform objective analysis in order to gain deeper understanding of the ongoing interaction between the robot and the human [200, 201]. Overall, it has become a common practice in interaction studies to back up findings with results from questionnaires with use of methods like conversation analysis [202]. We therefore also analysed the videos collected during interactions and created manual annotations. In this section we report two types of video analysis, the minimum distance of the participant from the robot and the reaction time. Due to the extensive effort required to analyse these videos we considered 15 participants from each condition, in total 30 videos/participants were analysed.

6.6.1 Minimum Distance

To measure the minimum distance we marked the floor with semi-circles measuring 0.5, 0.75, 1.0, 1.25 and 1.50 meters respectively with the robot placed in the center (Figure 6.10a). We then took a picture of the setup and colour coded and labelled the marked regions on the floor with distance measurements (Figure 6.10b). We then reduced the opacity of this picture to 40% and superimposed it on the videos matching features of the background video. This allowed us to observe the movement of the participant and the feet landing on the labelled zones, by pausing the video (Figure 6.10). We recorded the the minimum distance for each participant and the robot for the 3 tasks (greeting, message, call) in each condition (social, neutral robot behaviour).

(a) Floor distance markings



(b) Floor labels and colour coding

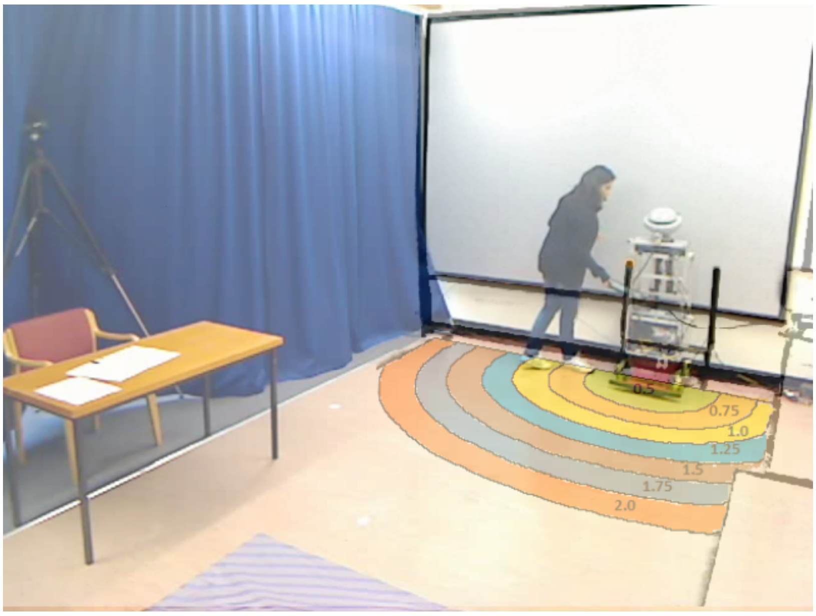


Figure 6.10: Picture overlay on video

An example video can be seen at `http://www.macs.hw.ac.uk/~amol/download/phd/DistanceMeasurement.mp4`

6.6.2 ELAN Annotation

A recent study by Alvin et al. [203] suggested that even in situations where the human is not actively interacting with a robot, the attention systems of the brain are active. So we decided to investigate the multi-modal interplay of the interaction in terms of reaction time to the robot. A method using the video annotation software ELAN [204] was used to annotate the time intervals (reaction time) between speech and motion for both human and robot. All annotations were analysed by using Matlab [205]. This gave us a higher level insight into the social interaction between the human and the robot (Figure 6.11). Therefore, the following rules were created. The highlighted rules are the ones which have been taken into account in the final analysis.

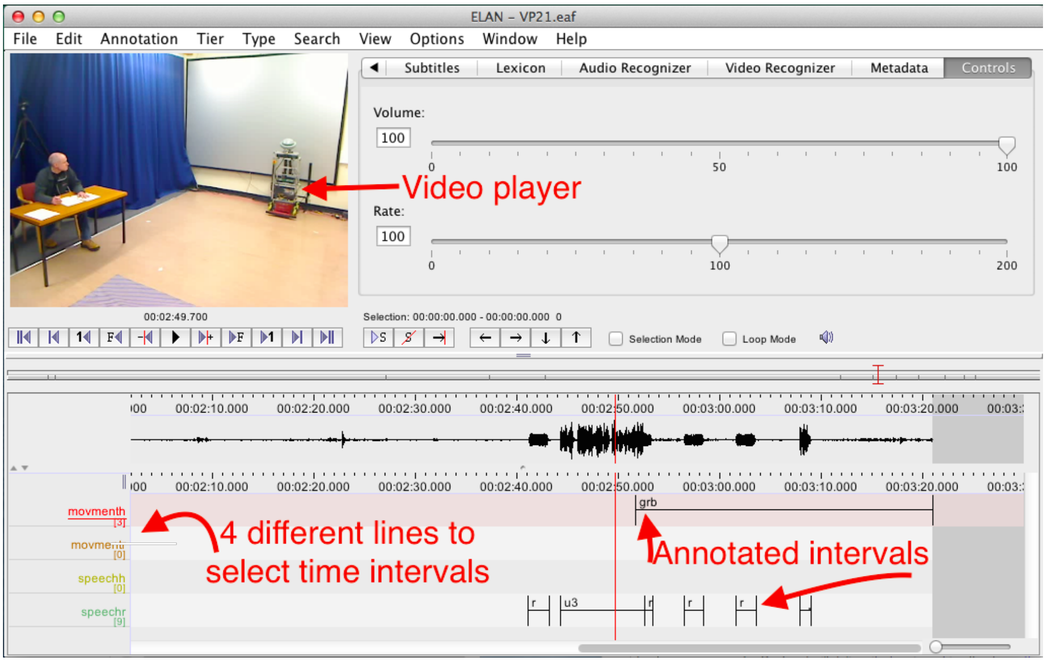


Figure 6.11: ELAN annotation screen.

These annotation rules described the social interaction between the robot and the human on a higher level as they include knowledge about the scenario and objects placed in the environment. Hence, the two annotations carried out on the video data deliver bottom up (2D location) and top down (scenario) information. Evaluating human-robot interaction from both sides: bottom and top levels of interaction has been proven to be important to gain a better understanding of an interaction [206], [207]. Furthermore, the ELAN annotations were imported into Matlab.

These were based on the annotated time intervals of the human movement (tier movement h) and the annotated intervals for the spoken utterances presented by the robot (tier speech r). The *reaction time* was calculated. We define the *reaction time* as the time interval the human took to respond to the robot's utterance. The *reaction time* was calculated based on the end point of the greeting, message and call utterance

from the robot (u1, u2, and u3) and the start of the annotated interval presenting a response from the participant to it (i.e., 'gtr', 'gdb', 'gr').
Annotation rules:

tier: movement h:
sd = sitting down
gtr = getting tablet from r
btr = bring tablet to r
gr = going to robot not picking up tablet
gu = getting up
grb = going to robot not picking up tablet and back to the desk
grbn = gdb but no interaction with the tablet

tier: movement r:
s2i = start to interaction pos
i2s = interaction to start pos

tier: speech h
spoken utterances

tier: speech r
u1 = greeting
u2 = message
u3 = call
r = phone ring
u4 = i got your message for Paul
u5 = Ok i got it
u6 = sorry my responses are limited, i didn't understand you
u7 = you can put the tablet back on me once you are done using it

6.7 Video Analysis Results

In this section, the results of the participants' behaviour, based on the annotations created are presented. First, the minimum distance for the movement between the robot and the human was examined presented in Section 6.7.1. Secondly, the participant's response to the robot's utterance for the message delivery and the call delivery were taken into consideration (Section 6.7.2). The results in this section investigates our hypothesis, *H2: The social robot will be preferred by people and will have a positive influence on peoples' perception of the robot more than the neutral robot while the robot is recharging.* We performed video analysis for the minimum distance and reaction time for stationary condition only as the movement of the robot in mobile condition may have influenced the distance and reaction time.

For our analysis we conducted a factorial ANOVA using the minimum distance, reaction time of the robot as the dependent variable, an ANOVA with condition (Social and Neutral robot behaviour) as a between-subjects factor and task (greeting, message and call) as a within-subjects factor. Followed up with analysis using Bonferroni (alpha = .05) was performed to examine the user's movement and reaction time in response to robot's behaviour in this section.

6.7.1 Distance: Minimum distance Results

We present the results for the minimum distance to the human in relation to the robot for each of the stationary cases (social and neutral). Table 6.8 summarises the results for the minimum distance, condition (social, neutral), Mean, Standard deviation (SD), Standard error mean (SE), F value and p-value. Figure 6.12 shows the mean minimum distances for the 3 tasks (greeting, message and call) in social and neutral conditions. The Y-axis on the graph describes the distance in meters.

There was a significant main effect for task (greeting, message, call) in the stationary robot condition, $F(1,28) = 6.813, \rho = .014, \eta_p^2 = .196$. This implies that there was a significant difference in the minimum distance of the participants from the robot during the stationary robot behaviour for each task. Post hoc analysis revealed that there was a significant difference between the greet ($M = .64$) and the call ($M = .72$) task, $\rho = .043$. This suggests, participants went closer to the robot during greeting task in comparison to call task. No significant differences were found between other tasks.

Task	**Condition**	**Mean**	**SD**	**SE**	**F(1,28)**	**p**
Greeting	Neutral	.73	.11	.029	10.377	.003
	Social	.55	.18	.047		
Message	Neutral	.73	.14	.038	1.806	.190
	Social	.66	.12	.031		
Call	Neutral	.78	.12	.033	6.472	.017
	Social	.66	.12	.031		

Table 6.8: Minimum distances results

Also there was a significant effect on condition between Social and Neutral conditions across tasks $F(1,28) = 9.822, \rho = .004$. There was a significant difference in the

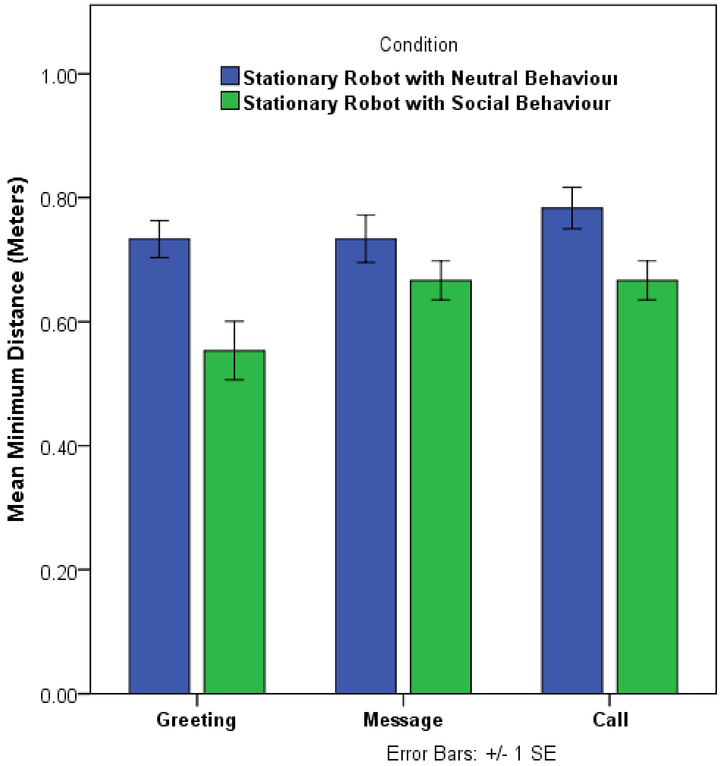


Figure 6.12: Minimum human-robot distance, N=15

minimum distance for greeting task between the Neutral: $M = .73, SE = .11$ and Social: $M = .55, SE = .18$, $F(1, 28) = 10.377, \rho = .003$ conditions. Also significant difference in the minimum distance for call task between the Neutral: $M = .78, SE = .12$ and Social: $M = .66, SE = .12$, $F(1, 28) = 6.472, \rho = .017$ conditions. However, no significant difference for the message delivery task. Thus, the participants who were exposed to the robot behaving more socially tended to stay closer to the robot during the greeting and the call task. Also the participants stay closer to the robot for all 3 tasks when the robot used social verbal utterances. Hence this result supports our hypothesis *H2*.

6.7.2 Reaction Time: ELAN Results

Based on the ELAN annotation described earlier, the *reaction time* of the participants after the robot's utterances was calculated. In detail, the timespan between the end of the utterance when the robot greeted, delivered a message and delivered a call to the participant and the moment when the participant stands up to answer was calculated. The Y-axis on the graphs describes the reaction time in milliseconds. We conducted a factorial ANOVA in our analysis, using the reaction time of the human as the dependent variable, an ANOVA with condition (Social and Neutral robot behaviour) as a between-subjects factor and task (greeting, message and call) as a within-subjects factor.

Reaction time:

There was a significant main effect for task, $F(2, 46) = 7.93, \rho <= .001, \eta_p^2 = .263$. This means there was a significant difference between each task in terms of reaction time. Looking at post hoc analysis, there was a significant difference between the greeting ($M = 11261.38, SE = 2261.27$) and call ($M = 76658.00, SE = 19380.01$) task $\rho = .010$. There were no significant differences for the other tasks, message and call.

This result may due to the fact that greet was the first task (before they started marking the exam paper) the robot performed after the participants arrived in the experiment room so they might have felt obliged to respond the the robot's greet behaviour faster than other tasks. Also the participants were marking the exam paper when the robot performed the message and call task which might have influenced their reaction time. Figure 6.13 describes the reaction time for the human to respond to the robots task presentation (greeting, message, call) when the robot was stationary. The Y-axis on the graph describes the reaction time in milliseconds.

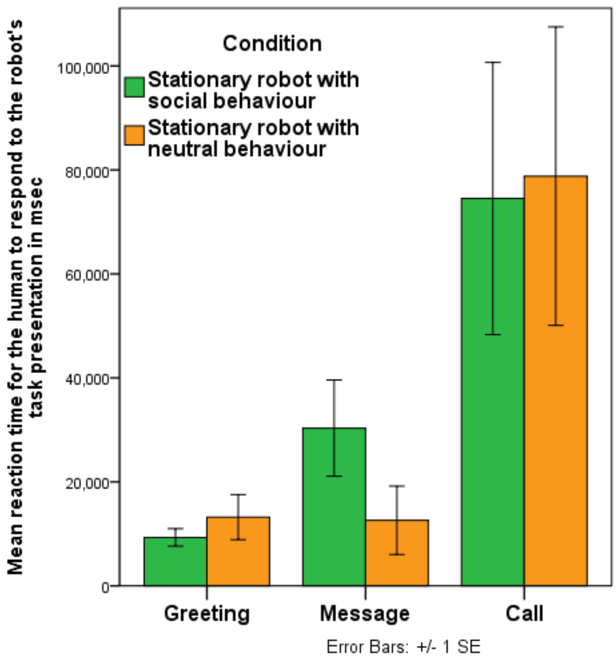


Figure 6.13: Reaction Time: Social vs. Neutral, N=15

There was no significant interaction between task × condition (social and neutral), $F(2, 46) = 0.26, \rho = 0.78, \eta_p^2 = 0.01$. Also there was no significant main effect for condition, $F(1, 23) = 0.07, \rho = 0.79, \eta_p^2 = 0.003$. Hypothesis *H2* was not fully supported in terms of reaction time. However the the reaction time for greet task during social ($M = 9304.76, SE = 3133.30$) condition was faster than neutral ($M = 13218.00, SE = 3261.25$) condition. Also the reaction time for call task, social ($M = 74511.00, SE = 26853.73$) condition was faster than neutral ($M =$

$78805.00, SE = 27950.25$) condition.

6.7.3 Summary Video Analysis

We present the main findings from video analysis presented in this section:

1. **Minimum Distance:** During the stationary case (recharging), significant results were found for condition (Figure 6.12). The participants tended to stay closer for the social condition, especially during the greeting and call task. So the use of verbal utterances did influence the minimum distance of participants from the robot. Hypothesis *H2* was supported in this case.

2. **Reaction Time:** The reaction time of the participants was faster (although not significant) when the robot was behaving more socially (polite, apologetic) towards the participants when it was stationary, except for the message delivery task. However, for social task like greeting, the reaction time was significantly faster then call task.

Based on these results one could argue that introducing social utterances by the robot (while recharging) which are more explanatory, polite and apologetic, can be adopted as an approach to make it more acceptable to the people during recharge. Furthermore, the social utterances seem to encourage the participants to support the robots limitation of movement during recharging by reacting faster as well as getting closer to it (especially for a social task like greeting).

6.8 Discussion

We presented questionnaire and video analysis from our study in this chapter. Using both subjective and objective measures helped to verify interpreting participants responses/behaviour in depth when interacting with the TB. From this study, first we wanted to investigate if people recognise a regression in service quality when the robot goes to recharge. Thus in Part A of the study the TB was operating normally (mobile) while performing tasks. However, in Part B of the study, when the TB was immobile while it was recharging (the TB had a limitation) we investigated how this impacts its acceptance and perception from the participants. The hypotheses proposed for this study *H1, H2* were supported in most cases from the results. Table 6.9 provides a summary of results from the questionnaire and video analysis in regards to the proposed hypotheses for the study.

The results from the questionnaire analysis Section 6.3 indicated that the people recognised a regression in service quality when the robot went to recharge and rated the stationary robot lower than mobile robot (Section 6.4) on task and social presence

Table 6.9: Results summary: $^{+}$ indicates higher mean rating in support of hypotheses, $^{-}$ indicates the hypotheses was not supported, * indicates statistical significance ($\rho <$ .05) and $^{-*}$ indicates contradiction to the hypotheses.
H1: People recognise a regression in service quality when the robot goes to recharge.
H2: The social robot will be preferred by people and will have a positive influence on peoples' perception of the robot more than the neutral robot while the robot is recharging.

Questionnaire Analysis		
Factor	**Measures**	**Hypothesis**
Tasks	Greeting	$H1^{-}$, $H2^{+}$
	Message	$H1^{*}$, $H2^{+}$
	Call	$H1^{*}$, $H2^{+}$
	Usefulness	$H1^{*}$, $H2^{+}$
Social Presence	I noticed the TB	$H1^{*}$, $H2^{-*}$
	TB presence was obvious to me	$H1^{*}$, $H2^{-*}$
	TB noticed me clearly	$H1^{*}$, $H2^{-*}$
	My presence was obvious to TB	$H1^{-}$, $H2^{-*}$
	Companionship	$H1^{*}$, $H2^{*}$
	Politeness	$H1^{*}$, $H2^{-}$
Open Questions	Part A/B, Q1-Q5	$H1^{+}$, $H2^{+}$
Video Analysis		
Factor	**Scale**	**Hypothesis**
Proximity	Minimum Distance	$H2^{*}$
ELAN-Reaction Time	Greeting	$H2^{+}$
	Message	$H2^{-}$
	Call	$H2^{+}$

scales. This indicates that when the TB had a limitation it does negatively influence the acceptance of the robot. This result is also similar to a previous study by Syrdal et al. [58] where immobility from the robot was negatively perceived by the participants in comparison to a mobile robot having similar behaviours. However, the authors did not investigate any approaches to manage the negative perception of users when the robot was immobile.

The results on task context also indicated that the type of task, social (greeting) or utility (message, call) appears to have an influence on participants ratings. Greeting is an important social norm in human-human interactions (Kendon [208]). Kendon found that a typical greeting behaviour between two individuals follows a structure of mostly non-verbal communications comprising phases; sighting, distance salutation, approach and finally close salutation. This indicates that greeting is influenced by proxemics. In our study, looking at comparison between the mobile and stationary condition, the greeting (a social task) was rated similarly for both conditions. This result might be because of the explanation (transparency) provided by the TB's about its limitation of not being able to move right at the start (greeting) of interaction set the right expectations for the participants.

Also from open questions (Section 6.5.3), 11 participants directly indicated that the verbal behaviour of the robot in terms of transparency (providing explanation) for not able to move to perform tasks was the best aspect. This indicates that transparency had a positive influence on participants perception about the TB's limitation of being immobile. There was a significant difference between the ratings for mobile and stationary condition for utility based tasks like message and call delivery. This indicates that the participants did not appear to accept the TB's limitation (recharging/immobile) for utility tasks (message, call). Criticism of the robot's recharge activity was also raised by participants during our long-term study (Chapter 5) from the interviews and user diaries. The TB spent a total of 55.10% of its time recharging and was unable to perform tasks or demonstrate social presence during recharge during our long-term study. This suggests the need to have a mitigation behaviour produced by the robot while recharging.

However, in our social study, when the robot was producing social verbal utterances while it was recharging (immobile), the mean ratings for message and call tasks were higher (but not significant) for social condition than the neutral condition. However, the other open questions (Section 6.5.3), the participants direct feedback suggests that, if the robot is able to perform verbal tasks and can convey its limitation/failures during recharge using verbal strategies (politeness, apology) then it would be more acceptable. From the video analysis 6.7.3, the participants went closer to the robot when the robot produced social verbal utterances in comparison when the robot produced neutral verbal utterances (significantly closer for greeting and call task). This indicates that the participants felt more comfortable with the robot producing social verbal behaviour and accepted it better. A previous study by Mumm & Mutlu [209], suggested that participants who disliked the robot compensated for the increase in the physical distance from the robot, while participants who liked the robot did not differ in their distancing from the robot. However, proxemics in HRI can be influenced by a number of factors, which includes a person's age, personality, familiarity with robots, and gender [210, 122]. We did not investigate the influence of these factors in our analysis.

The reaction time of the participants was faster (although not significant) when the robot was behaving more socially (polite, apologetic) towards the participants when it was stationary, except for the message delivery task. The reaction time for the greeting task was significantly faster than call or message task. Also from the questionnaire analysis 6.3 it was indicated that the participants rated the greeting tasks significantly higher than call or message task. The result from both video and questionnaire analysis indicates that type of task may have an influence on how participants behave with or perceived the TB. It appears that for a social task like greeting the acceptance of the TB was better than less social tasks like (message and call delivery) irrespective whether it was using social or neutral verbal utterances. The 3 tasks in this study had different levels of social component in it, for example greeting perhaps had more social component (Kendon [208]) than message delivery task (a less social task) and call delivery which was a more utility based task. This suggests that overall, people may accept the regression in service quality of robots depending on the social and utility aspect of the tasks the robot performs. Perhaps for utility tasks like call or message delivery the participants expected the robot to provide a better service in terms of mobility and also verbal behaviour (neutral robot was rated less as compared to social robot).

The overall results from our social study indicated that when the robot was unable to move while recharging, the use of verbal strategies, when the robot is polite, apologetic and more explanatory in conveying its limitations during recharging suggests that participants may accept it better, and will feel more comfortable in its company. However, the results from the social presence questionnaire contradicts our finding, this requires further investigation. Komatsu et al. showed in their study [14], the participants with positive adaptation gap (difference between the users' expectations and the function that the users' actually perceived of an agent) had a significantly higher acceptance rate than those with a negative adaptation gap. Hence, we believe managing user expectations in a socially appropriate manner may ease acceptance of robot's regression in service quality. However, the results from using social verbal utterances to manage user expectations need further work to confirm these findings.

6.9 Conclusion

In this chapter we reported a social study focusing the impact of verbal strategies and service degradation on people's acceptance of the robot. Modifying the verbal behaviour of the robot during recharge to our knowledge is a first attempt to explore feedback strategies from the robot in order to enhance the user's tolerance towards the robot's recharging behaviour. We proposed an approach to manage user's expectations concerning the verbal behaviour of a robot during recharging using verbal strategies and summarised key findings in this chapter (Table 6.9).

Managing user expectations of mobile robots becomes particularly challenging when the end-user is aware of the full capabilities of the robot. The user might expect good service from the robot and when the robot is unable to provide it, social robots should be capable of mitigating their limitations in a socially acceptable manner. The overall results from our study indicate that when the robot has a limitation, the use of verbal social strategies can help to manage users expectations. Hence keeping the users informed about the robots limitations can help to mitigate the disappointment of not being able to provide service normally.

Although the findings in this study may have been influenced due to repeated interaction with the robot (participants interacted twice with the robot during our study within a short time span), a familiarisation effect [211], familiarity may also ease social acceptance. Also the fact that some participants had to walk a greater distance towards the robot during recharging/stationary condition in comparison to the mobile condition may also have influenced the perception and behaviour towards the robot. We believe, the results from this short-term experiment can provide useful design considerations for social companion robots to manage their recharge behaviour. We envisage, the use of verbal transparency to manage the recharge behaviour during long-term operations can help to mitigate users' disappointment in a socially intelligent manner.

Chapter 7

Conclusions

In thesis we investigated the impact of service degradation in long-term human-robot interaction with particular reference to recharge behaviour. We also proposed an approach based on verbal behaviour of the robot while recharging, which helped to manage user expectations in a socially intelligent manner. In this thesis we followed an approach based on user-centric design which helped us to make iterative improvements to the system (Chapter 3 Section 3.4). Investigating robot-human interaction from a human-centred perspective allowed us not only to understand the technological challenges for long-term HRI, but also the social implications of the recharge behaviour of our robot. We developed capabilities for the robot in regards to hardware (height, additional sensors, batteries) and tasks (autonomous navigation and recharging) it could perform in an office environment for long-term period in a robust manner (Chapter 3, Section 3.5). Previous approaches on auto-recharging (Chapter 2, Section 2.2.2) helped to guide our approach to develop robust auto-recharging capabilities for our robot.

We started by carrying out two pilot experiments (described in Chapter 4), the first experiment was to understand the power requirements and to test the robustness of the navigation capability of the robot, exhaustive navigation runs were performed. The navigation experiment helped to decide the appropriate threshold voltage value for the robot to initiate recharge. The noise from the sonar scanner and the higher speed of the robot were modified (reduced navigation speed and switching off navigation after navigation was completed) and we found later from our long-term study that these modifications helped the robot to be more socially acceptable in regards to its navigation around the office environment. Previous studies have indicated that navigation speed of the robot does influence the perception of mobile robots [212, 155, 213] hence the navigation speed of the mobile robot needs special attention by robot designers.

The second pilot experiment was a long-term experiment focused to test the robustness of the overall system. The feedback received from the participants resulted in improving the system, especially the recharge behaviour and adding verbal transparency to the robot (notifying the users about recharge). We used fuzzy logic for battery voltage indication, which provided a better approximation about the battery levels as we found in our long-term study in Chapter 5). Shutting down system components upon identification of a successful dock also resulted in a faster and more efficient recharging cycle time. It is important to take into account not just the technical challenges but also the social issues while developing social mobile robots for long-term operation. Systematic modifications were made to our robot taking into account both the social and technical issues raised during these pilot experiments. These improvements further enhanced our approach and assisted to develop a more robust recharge mechanism vital for the long-term operation of the robot.

With an improved system we preformed long-term experiment with 5 participants in an office environment for 3 weeks. This was a qualitative study which allowed us to investigate the recharging aspects of the robot with a small group of participants. Conducting long-term studies with a large group of participants is challenging both technically and logistically. Having a small group of participants during our long-term study allowed us to capture and analyse intimate experience of the participants interactions and detailed feedback from them. The combination of several data collection methods (Sung et al. [117]) was extremely useful for capturing people's perception and interaction with the robot. Data was analysed from questionnaires, interviews, user diaries and system log files.

The results from our long-term study described in Chapter 5 highlighted the social and technical issues with the robot's recharge behaviour and how it negatively affected the overall interaction with the robot. The service degradation caused due to robot's recharging had a negative influence on the users perception and social acceptance of the mobile robot. The robot lacked coping mechanisms to manage/mitigate its limitation which appeared to have disappointed the participants. The disengagement of users from the robot due to recharging has also been found to be influential in other long-term HRI studies [115, 111]. The robot during the long-term study spent 56% of the time at the charging station impeding the flow of interaction with the participants. The participants mentioned (from interviews and diaries) their disappointment with the robot for recharging for a long time and not being available to perform tasks. Although, the results from our long-term study were not statistically significant due to the small sample size, we believe that participants' feedback on recharge issues should be considered in design process of mobile social robots. Finally, we made some design recommendations following our long-term study (Section 5.4) on autonomous recharging (Selecting an appropriate recharge time, Recharge duration, Behaviours while recharging, Social positioning for recharging); Managing user expectations using transparency, notifying the users about its recharge intentions by either verbal or non-verbal behaviour to set the right expectation for the users; and Power management, which can help extend the operational time of the mobile robot. We believe that these recommendations can provide useful design considerations for recharging behaviour for mobile robots.

The important and fundamental issue of robot's recharge behaviour does not appear to be widely addressed in the social robotics domain. A mismatch between the users' expectations and the social intelligence of the robot can negatively impact acceptance and use of the robot [176, 177]. Because the problem of recharging for mobile robots from a fixed position does not appear to have an appropriate engineering solution, a social solution seemed viable to manage users' expectations. It became apparent that recharging activity of the robot needs to be managed more appropriately for the robot to be an acceptable long-term social interaction partner. We interpreted that the immobility of the robot and not performing verbal tasks while recharging may have influenced the negative perception of our robot.

We then specifically investigated people's perception on regression in service quality when the robot goes to recharge and the verbal behaviour of the robot while recharging by means of a social study (Chapter 6). We explored the use of verbal strategy using more transparent, polite and apologetic verbal utterances for during robot's recharge. To collect a more generic opinion we performed a quantitative social study with 50 participants. In this study we focused on investigating the regression in service quality and social verbal behaviour of the robot during recharging. The results indicated that mobility of the robot was more preferred by users in terms service, usefulness and social aspects like politeness and companionship of the robot. The type of task also had an influence on participants ratings. The more social task like greeting does not appear to have significant negative influence on user's ratings in comparison to utility based task like message or call delivery. Greeting in human-human interaction serves an important social function (Kendon [208]), same is also true in human-robot interaction [214, 215]. This indicates that when the robot is undergoing a regression in service quality when the robot goes to recharge (being immobile) then the utility aspect of the robot may be negatively perceived by the users.

Nevertheless, the fact that the robot still managed to perform verbal tasks while recharging was rated by majority of the participants as the best aspect of the TB during recharging. This suggests that social mobile robots could still perform verbal tasks while recharging which could help to ease their acceptance. However, there could be inter-personal differences between individuals how they perceive mitigation behaviour from the robot to manage its limitation. A previous study by Lee et al. [15], indicated that, people who have a more relational orientation or social schema, desire to maintain a good relationship with a service provider, even when there is service breakdown. Whereas, people who have a strong utilitarian orientation but a low relational orientation might treat a robot as a social service provider, and expect it to apologise after a mistake. We did not investigate the influence of relational/utilitarian orientation of users on service limitation in our study [15].

Also during recharge if the mobile robot has a head/face then the position of the robot may matter as 8 participants in our study did not like the robot facing towards wall during recharge. However 4 participants were more comfortable with the robot not facing them during recharge. A study by Takayama & Pantofaru [210] suggested, when the robot's head was oriented toward the person's face, it had an influence the minimum comfortable distance from the robot. Women in their study stood further away than men from the robot when its head was facing their faces. This indicates that the users might have a personal preference if the robot is facing them (may be due to privacy issues as the robot head had a camera) during recharge in our study. Head orientation of the robot was not the focus of our investigation.

In terms of position of the robot during recharge, a study by Fink et al. with Roomba at homes (vacuum cleaning robot) suggested some people did not want to have either the robot or its charging station visible in a prominent open space, such as the living room [118]. Robots and humans sharing the physical same space, need to adapt to each others technical and social requirements. This suggests that careful consideration is necessary while deciding a socially best placement for recharging (Lindner [35]) by mobile robots. Also Roomba robot hardly has any social interaction capabilities and is much smaller in size (crawls along the floor) than other social mobile robot platforms used in social environments for example Peoplebot [52], Scitos [57] robots. We believe that the social implications with bigger mobile robots and its recharge position and orientation requires attention from robot designers.

Robots are becoming increasingly autonomous in our environments, but they still must overcome technical limitations like recharging while giving service to humans. While some work has focused on robots that request help from humans to manage their limitations [144, 124, 216, 217]. These studies assumes that humans are supervising the robot and always available to help, this may not be always true especially in workplace environment where people can be busy with their own work [218]. We argue that designing a proactive socially appropriate mitigation strategy to manage user expectations is necessary for mobile robots to be acceptable.

Komatsu et al. [14] suggested from their study that when perceptions of an agent exceed users' expectations, it can ease their social acceptance. Previous studies indicate that people's beliefs would be influenced by expectation-setting strategies used in presenting robots (Paepcke & Takayama [13], Lohse [40]). Also forewarning people can mitigate the negative influence of breakdown on service satisfaction (Lee et al. [15]). We believe that our approach combines earlier work in terms of transparency [14], verbal strategies [15] and expectation setting strategies [13]. The results from our social study indicate that when the robot has a limitation, keeping the users informed about its limitation in a socially acceptable manner can help to manage users expectations and increase their tolerance to service degradation.

7.1 Limitations

The work in this thesis is more applicable for long-term interaction with social mobile robots. Short term interactions may not have issues with robot recharge as they can be recharged manually during sessions. The social context of a robot that serves humans is likely to impact how people will behave in the robot's presence and perceive the recharge behaviour. This context may vary considerably depending on the scenario used, the type of robot, appearance of the robot [219] and the purpose of the robot over shot-term or long-term. For example robots deployed in malls [109], museums [107, 4], educational settings [110, 112, 111] etc. where the only purpose of the robot is to engage people in short-term interaction may not need to manage issues with recharging.

However, the social context of long-term human-robot interaction in domestic ([115, 118]) and workplace environments (e.g. [103, 104, 220, 218, 105]) is different as the robot may need to share the same physical space with the users. There are a variety of robot characteristics that may influence social acceptance [176], such as the robot's function (tasks performed), social ability (emotion expression), robot form/appearance (human-likeness, gender) etc. Also user's personality, cross-cultural and gender differences could influence acceptance of social robots. The work in this thesis did not take these effects (social context, robot characteristics, personality, gender) into consideration, future work can take into account these issues.

The work in this thesis is more relevant to single mobile robot interacting in a shared physical space with human users. Having multiple robots (not always practical) in the same physical space sharing service time may not have the same issues as pointed in this thesis. Also emerging technologies like fast charging solutions [60], and improving battery technology may help to fully charge in a matter of minutes, rather than the several hours in the case of a conventional battery. However, these emerging recharging solutions seem years away and expensive to put into use for current state-of-the-art mobile robots. Hence we proposed an approach in this thesis that can help to manage user expectations in a socially intelligent manner during recharge.

7.2 Future work

Since the issue of recharging from a fixed position does not appear to have an appropriate engineering solution, one could explore other ways to manage user expectations and the recharge behaviour of the robot. We have summarised a few areas one could investigate as follows.

- We explored the use verbal strategies in our social study using apology, polite (Chapter 6) and the results indicated that the participants accepted it better during recharge. However, our social study was conducted in short term interaction context. One could further investigate the use of these verbal strategies (polite, apologetic and more explanatory in conveying its limitations) during a long-term study to explore how the users perceive it. Previous long-term HRI studies have indicated that a novelty effect influences users perception of the robot [210]. The impact of verbal strategies during recharging in long-term interaction is still an open question.

- During our long-term and social study, due to the position of recharge connector of our robot, the robot was always facing towards the charging station (towards the wall). Feedback from some of the participants indicated from that this may have influenced the perception of the robot. One could explore further the aspect of socially appropriate positioning for recharging [35, 210]. How does positioning/orientation of the robot impact the social perception of the the robot while recharging can be a valid avenue for further investigation [118].

- It is important for a social robot to keep track of users and understand basic user activities in order to initiate and interact with them. We developed user monitoring capabilities for the robot which can help the robot to perceive user presence information like Entry, Exit, Break (Chapter 3, Section 3.8). Selecting an appropriate recharge time based on users' presence patterns can help to improve the robot's availability. One could use a machine learning approach to develop a mechanism for the robot to effectively learn the presence patters of the users and select the ideal time for the robot to recharge when it expects the users to be absent.

- One could address the challenge of recharge with more elaborate power management for enhancing the operational time of mobile robots. Power savings can be achieved by adapting the sensing rate when the robot is running low on power or expects less user interaction. Hence, we proposed some recommendations in relation to power management and combining it with machine learning (detect user presence patterns), which can lead towards power efficient long-term operation of social mobile robots (Chapter 5, Section 5.4). Further experiments could be conducted to investigate the impact of these recommendations on the power savings of the mobile robot.

- The recommendations based on autonomous recharging reported in Chapter 5, Section 5.4 can be incorporated in the robot design. The recharge time could vary according to the priority (utility vs social) of pending tasks. The robot instead of doing a full recharge (taking a longer time) could do a short recharge and finish its pending tasks and come back to recharging. Also adding idle behaviours while recharging (verbal/non-verbal) may help to increase its perceived social presence. One could further investigate the impact of these factors on social acceptance of the robot.

7.3 Contributions and Achievements

The work presented in this thesis makes novel contributions to managing expectations while a robot is undergoing a regression in service quality and recharge issues during long-term human-robot interaction. Most importantly our work proposes an approach to address the challenges arising during long-term interaction with robots in regards to the recharge activity. We believe that our work makes novel contributions to HRI in the following ways.

- We developed robust navigation, auto-recharging capabilities which allowed the mobile robot to operate in a social environment for 3 weeks without any major failures. Autonomous long-term operation of mobile robots in social environments is very challenging. During our long-term study, the robot had only one docking failure and only 5 breakdowns in total. The robustness of the system enabled us to conduct a successful long-term study in real settings and thereby allowed us to collect valuable feedback on recharge behaviour of the robot.

- Exploratory pilot studies (Chapter 4) provided useful insights in understanding the social considerations (lower navigation speed desired by participants) and reducing noise levels by the robot once navigated near the user. We also improved the recharging mechanism by implementing an approach using fuzzy logic to indicate voltage levels; installation of flash light to manage changing light conditions (for finding docking station); shutting down some components not required while recharging which helped to reduce the recharging time. We believe these approaches are novel to the HRI domain and can be considered in the design process for developing recharge mechanisms.

- We carried out a long-term study (within the scope of LIREC project) where the robot was operating fully autonomously in a social environment. To our knowledge this is perhaps one of the longest HRI study in Europe where the mobile social robot shared the same physical space as the participants for 3 weeks and investigated the impact of recharge behaviour of the robot. Feedback received from our participants from our long-term study produced novel understanding about the social implications of recharge activity of the robot. It appears from our literature survey that no long-term HRI studies carried out in natural settings have investigated in depth the impact of recharge behaviour of a mobile robot in a social context.

- Design recommendations derived from our work are proposed in Chapter 5, Section 5.4 which can be useful for managing the recharge behaviour of social mobile robot in socially appropriate manner. We also proposed some ideas for power management for potential power savings on social mobile robots which appears to be novel for HRI field.

- Novel results were produced from our social study which provided deeper understanding about user's attitudes towards a mobile robot with respect to recharge activity and how the robot's verbal behaviour can influence perception and acceptance of the robot. Modifying the verbal behaviour of the robot is perhaps the first attempt to explore feedback strategies from the robot in order to enhance the user's tolerance for the robot's service degradation due to recharging. The direct feedback received from the participants from our social study (reported in Appendix A, Section **??**)) to the best of our knowledge is a first attempt to collect detailed feedback on recharge behaviour of a social mobile robot.

The work in this thesis has been published at several events as described in Appendix A. 9.

7.4 Summary

This thesis investigated the impact of service degradation caused due to recharge behaviour of a robot while interacting with users. We proposed a social solution to a technical problem of recharging from a fixed position. The results from our social study can provide useful design considerations for social companion robots to manage user expectations during recharge. We anticipate that social mobile robots having a socially intelligent behaviour during recharge will be more acceptable to the users. We believe that the work described in this thesis is generalisable to other domains where good social engineering can help to mitigate technical limitations of social robots.

References

[1] Chenghui Cai, Dong Du, and Zhiyu Liu. Advanced traction rechargeable battery system for cableless mobile robot. In *Advanced Intelligent Mechatronics, 2003. AIM 2003. Proceedings. 2003 IEEE/ASME International Conference on*, volume 1, pages 234–239 vol.1, July 2003.

[2] Se gon Roh, Jae Hoon Park, Young Kouk Song, Kwang Woong Yang, Moosung Choi, Hong-Seok Kim, Hogil Lee, and Hyouk Ryeol Choi. Flexible docking mechanism using combination of magnetic force with error-compensation capability. In *Automation Science and Engineering, 2008. CASE 2008. IEEE International Conference on*, pages 697–702, Aug 2008.

[3] R.C. Luo, C.T. Liao, K.L. Su, and K.C. Lin. Automatic docking and recharging system for autonomous security robot. In *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on*, pages 2953–2958, Aug 2005.

[4] Illah R Nourbakhsh, Judith Bobenage, Sebastien Grange, Ron Lutz, Roland Meyer, and Alvaro Soto. An affective mobile robot educator with a full-time job. *Artificial Intelligence*, 114(1):95–124, 1999.

[5] Vincent Tabak. *User simulation of space utilisation: system for office building usage simulation.* PhD dissertation Eindhoven University of Technology., 2009.

[6] http://tinyurl.com/o5ybowg. World robotics report, 2014.

[7] M. Heerink, B. Krose, V. Evers, and B. Wielinga. Measuring acceptance of an assistive social robot: a suggested toolkit. In *Robot and Human Interactive Communication, 2009. RO-MAN 2009. The 18th IEEE International Symposium*, pages 528–533, Sept 2009.

[8] Bilge Mutlu and Jodi Forlizzi. Robots in organizations: the role of workflow, social, and environmental factors in human-robot interaction. In *Human-Robot Interaction (HRI), 2008 3rd ACM/IEEE International Conference on*, pages 287–294. IEEE, 2008.

[9] Mary Jo Bitner, Bernard H Booms, and Mary Stanfield Tetreault. The service encounter: diagnosing favorable and unfavorable incidents. *The Journal of Marketing*, pages 71–84, 1990.

[10] GZ Qian and K Kazerounian. Statistical error analysis and calibration of industrial robots for precision manufacturing. *The International Journal of Advanced Manufacturing Technology*, 11(4):300–308, 1996.

[11] Joseph F Engelberger. *Robotics in practice: management and applications of industrial robots*. Springer Science & Business Media, 2012.

[12] Masahiro Mori, Karl F MacDorman, and Norri Kageki. The uncanny valley [from the field]. *Robotics & Automation Magazine, IEEE*, 19(2):98–100, 2012.

[13] Steffi Paepcke and Leila Takayama. Judging a bot by its cover: an experiment on expectation setting for personal robots. In *Human-Robot Interaction (HRI), 2010 5th ACM/IEEE International Conference on*, pages 45–52. IEEE, 2010.

[14] Takanori Komatsu, Rie Kurosawa, and Seiji Yamada. How does the difference between users' expectations and perceptions about a robotic agent affect their behavior? *International Journal of Social Robotics*, 4(2):109–116, 2012.

[15] Min Kyung Lee, Sara Kiesler, Jodi Forlizzi, Siddhartha Srinivasa, and Paul Rybski. Gracefully mitigating breakdowns in robotic services. In *Human-Robot Interaction (HRI), 2010 5th ACM/IEEE International Conference on*, pages 203–210. IEEE, 2010.

[16] Kerstin Dautenhahn. Socially intelligent robots: dimensions of human–robot interaction. *Philosophical Transactions of the Royal Society B- Biological Sciences*, 362(1480):679–704, 2007.

[17] Ruth Aylett. *Robots: Bringing Intelligent Machines To Life.* Barrons, 2002.

[18] Oh. A., Zelinsky, and K A., Taylor. Autonomous battery recharging for indoor mobile robots. In *In Australian Conference on Robotics and Automation*, 2000.

[19] J. Dimas, I. Leite, A. Pereira, Rui Prada P. Cuba, and A. Paiva. Pervasive pleo: Long-term attachment with artificial pets. In *MobileHCI 2010*. Lisboa, Portugal, September 2010.

[20] Elena Pacchierotti, Henrik I. Christensen, and Patric Jensfelt. Design of an office guide robot for social interaction studies. In *IEEE-RSJ International Conference on Intelligent Robots and Systems*. Beijing, China, October 2006.

[21] A brief guide. Electrical safety and you.

[22] Kerstin Dautenhahn. The art of designing socially intelligent agents: Science, fiction, and the human in the loop. *Applied artificial intelligence*, 12(7-8):573–617, 1998.

[23] Iolanda Leite, Ginevra Castellano, Andre Pereira, Carlos Martinho, and Ana Paiva. Long-term interactions with empathic robots: Evaluating perceived support in children. In *Social Robotics*, volume 7621 of *Lecture Notes in Computer Science*, pages 298–307. Springer Berlin Heidelberg, 2012.

[24] Peter H Kahn Jr, Takayuki Kanda, Hiroshi Ishiguro, Brian T Gill, Jolina H Ruckert, Solace Shen, Heather E Gary, Aimee L Reichert, Nathan G Freier, and Rachel L Severson. Do people hold a humanoid robot morally accountable for the harm it causes? In *Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction*, pages 33–40. ACM, 2012.

[25] Marc Hanheide, Manja Lohse, and Hendrik Zender. Expectations, intentions, and actions in human-robot interaction. *International Journal of Social Robotics*, 4(2):107–108, 2012.

[26] Jonathan L Herlocker, Joseph A Konstan, and John Riedl. Explaining collaborative filtering recommendations. In *Proceedings of the 2000 ACM conference on Computer supported cooperative work*, pages 241–250. ACM, 2000.

[27] Taemie Kim and Pamela Hinds. Who should i blame? effects of autonomy and transparency on attributions in human-robot interaction. In *Robot and Human Interactive Communication, 2006. ROMAN 2006. The 15th IEEE International Symposium on*, pages 80–85. IEEE, 2006.

[28] Joseph B Lyons. Being transparent about transparency: A model for human-robot interaction. In *2013 AAAI Spring Symposium Series*, 2013.

[29] Massimiliano Zecca, Yu Mizoguchi, Keita Endo, Fumiya Iida, Yousuke Kawabata, Nobutsuna Endo, Kazuko Itoh, and Atsuo Takanishi. Whole body emotion expressions for kobian humanoid robot—preliminary experiments with different emotional patterns—. In *Robot and Human Interactive Communication, 2009. RO-MAN 2009. The 18th IEEE International Symposium on*, pages 381–386. IEEE, 2009.

[30] Hagen Lehmann, MichaelL. Walters, Anna Dumitriu, Alex May, Kheng Lee Koay, Joan Saez-Pons, DagSverre Syrdal, Luke Wood, Joe Saunders, Nathan Burke, Ismael Duque-Garcia, Bruce Christianson, and Kerstin Dautenhahn. Artists as hri pioneers: A creative approach to developing novel interactions for living with robots. 8239:402–411, 2013.

[31] Kheng Lee Koay, MichaelL. Walters, Alex May, Anna Dumitriu, Bruce Christianson, Nathan Burke, and Kerstin Dautenhahn. Exploring robot etiquette: Refining a hri home companion scenario based on feedback from two artists who lived with robots in the uh robot house. 8239:290–300, 2013.

[32] Leila Takayama, Doug Dooley, and Wendy Ju. Expressing thought: improving robot readability with animation principles. In *Proceedings of the 6th international conference on Human-robot interaction*, pages 69–76. ACM, 2011.

[33] Celine Jost, Brigitte Le, and Pévédic Dominique Duhaut. Study of the importance of adequacy to robot verbal and non verbal communication in human-robot interaction. 2012.

[34] Jeremy Riviere, Carole Adam, Sylvie Pesty, Catherine Pelachaud, Nadine Guiraud, Dominique Longin, and Emiliano Lorini. Expressive multimodal conversational acts for saiba agents. 6895:316–323, 2011.

[35] Felix Lindner and Carola Eschenbach. Affordance-based activity placement in human-robot shared environments. 8239:94–103, 2013.

[36] Ning Wang, W Lewis Johnson, Richard E Mayer, Paola Rizzo, Erin Shaw, and Heather Collins. The politeness effect: Pedagogical agents and learning outcomes. *International Journal of Human-Computer Studies*, 66(2):98–112, 2008.

[37] Tatsuya Nomura and Kazuma Saeki. Effects of polite behaviors expressed by robots: A case study in japan. In *Proceedings of the 2009 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology-Volume 02*, pages 108–114. IEEE Computer Society, 2009.

[38] Bram Hendriks, Bernt Meerbeek, Stella Boess, Steffen Pauws, and Marieke Sonneveld. Robot vacuum cleaner personality and behavior. *International Journal of Social Robotics*, 3(2):187–195, 2011.

[39] Maha Salem, Micheline Ziadee, and Majd Sakr. Effects of politeness and interaction context on perception and experience of hri. In *Social Robotics*, pages 531–541. Springer, 2013.

[40] Manja Lohse. The role of expectations in hri. *New Frontiers in Human-Robot Interaction*, 2009.

[41] A Weiss, N Mirnig, and F Forster. What users expect of a proactive navigation robot. In *Proceedings of the workshop- Expectations in intuitive interaction on the 6th HRI International conference on Human-Robot Interaction*, 2011.

[42] Tsuyoshi Sasaki, Yoshio Ukyo, and Petr Novák. Memory effect in a lithium-ion battery. *Nature Publishing Group*, 12(6):569–575, 2013.

[43] http://www.mpoweruk.com/performance.htm.

[44] http://www.mobilerobots.com/researchrobots/researchrobots/p3at.aspx.

[45] http://www.yuasabatteries.com/pdfs/np_7_12_datasheet.pdf.

[46] http://www.irobot.com/for-the-home/vacuum-cleaning/roomba.

[47] http://asimo.honda.com/asimo-form/battery-power-supply/.

[48] http://robotic.media.mit.edu/projects/robots/mds/overview/overview.html.

[49] http://flash.iiar.pwr.edu.pl/.

[50] http://doc.aldebaran.com/1-14/family/robots/battery_robot.html#robot-battery.

[51] http://www.willowgarage.com/pages/pr2/specsy.

[52] http://www.mobilerobots.com/libraries/downloads/peoplebot-pplb-reva.sflb.ashx.

[53] http://www.robotshop.com/pdf/irobot-roomba-400-users-guide.pdf.

[54] http://www.care-o-bot.de/en/care-o-bot-3/hardware/technical-data.html.

[55] Takanori Shibata, Yukitaka Kawaguchi, and Kazuyoshi Wada. Investigation on people living with paro at home. In *Robot and Human Interactive Communication, 2009. RO-MAN 2009. The 18th IEEE International Symposium on*, pages 1131–1136. IEEE, 2009.

[56] http://www.pleoworld.com/pleo_rb/eng/index.php.

[57] Metralabs. http://metralabs.com/images/ml_downloads/flyer_scitos_a5.pdf.

[58] DagSverre Syrdal, Kerstin Dautenhahn, Kheng Lee Koay, MichaelL. Walters, and WanChing Ho. Sharing spaces, sharing lives - the impact of robot mobility on user perception of a home companion robot. 8239:321–330, 2013.

[59] http://www.aiai.ed.ac.uk/project/aibo/documents/ERS 7M2/AIBO-Basic-Manual.pdf. *User Guide - Aibo entertainment robot.* Online.

[60] Jinzhang Liu, Francesca Mirri, Marco Notarianni, Matteo Pasquali, and Nunzio Motta. High performance all-carbon thin film supercapacitors. *Journal of Power Sources*, 274:823–830, 2015.

[61] W Walter. The living brain. 1953.

[62] W Grey Walter. Imitation of life. 1950.

[63] S. Yuta and Y. Hada. Long term activity of the autonomous robot-proposal of a bench-mark problem for the autonomy. In *Intelligent Robots and Systems, 1998. Proceedings., 1998 IEEE/RSJ International Conference on*, volume 3, pages 1871–1878 vol.3, Oct 1998.

[64] Yasushi Hada and Shin'ichi Yuta. A first-stage experiment of long term activity of autonomous mobile robot — result of repetitive base-docking over a week. 271:229–238, 2001.

[65] Seungjun Oh and Alexander Zelinsky. Autonomous battery recharging for indoor mobile robots. In *In Australian Conference on Robotics and Automation*, 2000.

[66] R. Cassinis, F. Tampalini, P. Bartolini, and R. Fedrigotti. Docking and charging system for autonomous mobile robots. In *Tech. Rep. DEA, University of Brescia, Brescia, Italy*, 2005.

[67] N. Bowditch. *The american practical navigator*. 2002.

[68] M.C. Silverman, D. Nies, Boyoon Jung, and G. Sukhatme. Staying alive: a docking station for autonomous robot recharging. In *Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on*, volume 1, pages 1050–1055 vol.1, 2002.

[69] Kuo-Lan Su, Yi-Lin Liao, Shih-Ping Lin, and Sian-Fu Lin. An interactive auto-recharging system for mobile robots. *International Journal of Automation and Smart Technology*, 4(1), 2014.

[70] Francois Michaud, Jonathan Audet, Dominic Letourneau, Luc Lussier, Catherine Theberge-Turmel, and Serge Caron. Autonomous robot that uses symbol recognition and artificial emotion to attend the aaai conference. *AAAI Robot Competition Technical Report*, 2000.

[71] Eduardo R Torres-Jara. *A self-feeding robot*. PhD thesis, Citeseer, 2002.

[72] B. Mayton, L. LeGrand, and J.R. Smith. Robot, feed thyself: Plugging in to unmodified electrical outlets by sensing emitted ac electric fields. In *Robotics and Automation (ICRA), 2010 IEEE International Conference*, pages 715–722, May 2010.

[73] L. Bustamante and J. Gu. Localization of electrical outlet for a mobile robot using visual servoing. In *Electrical and Computer Engineering, 2007. CCECE 2007. Canadian Conference on*, pages 1211–1214, April 2007.

[74] Victor Eruhimov and Wim Meeussen. Outlet detection and pose estimation for robot continuous operation. In *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference*, pages 2941–2946, Sept 2011.

[75] Available: http://www.irobot.com. *Roomba cleaning robot with self-charging home base station.* Online.

[76] Michele Marostica, Marco Bullo, Michele Moro, Fabrizio Dughiero, and Emanuele Menegatti. A wireless recharging system for electrical agriculture robots with autonomous docking. In *International workshop collocated with the 13th International Conference on Intelligent Autonomous Systems*, 2013.

[77] Jae-O Kim, Sunny Rho, Chan-Woo Moon, and Hyun-Sik Ahn. Imaging processing based a wireless charging system with a mobile robot. 352:298–301, 2012.

[78] *Applied AI Systems Inc., Continuous Power Supply for Khepera, Product Literature, Kanata, Ont.* 1998.

[79] A. Martinoli, E. Franzi, and O. Matthey. Towards a reliable set-up for bio-inspired collective experiments with real robots. In *Proceedings of the Fifth Symposium on Experimental Robotics ISER-97*, pages 597–608. Springer Verlag, 1997.

[80] Guangming Song, Hui Wang, Jun Zhang, and Tianhua Meng. Automatic docking system for recharging home surveillance robots. *Consumer Electronics, IEEE Transactions on*, 57(2):428–435, May 2011.

[81] Jun Zhang, Guangming Song, Yuya Li, Guifang Qiao, and Zhiwen Li. Battery swapping and wireless charging for a home robot system with remote human assistance. *Consumer Electronics, IEEE Transactions on*, 59(4):747–755, November 2013.

[82] Nilanjan Banerjee, Ahmad Rahmati, MarkD. Corner, Sami Rollins, and Lin Zhong. Users and batteries: Interactions and adaptive energy management in mobile systems. 4717:217–234, 2007.

[83] EVA-MARIA EMSENHUBER. Determinants of the acceptance of electric vehicles-an empirical analysis. In *MASTER THESIS IN MARKETING.*

Online:http://pure.au.dk/portal-asb-student/files/50709099/THESIS.pdf, 2012.

[84] Robin Segal. Forecasting the market for electric vehicles in california using conjoint analysis. pages 89–111. JSTOR, 1995.

[85] Susanne Frennert, Håkan Eftring, and Britt Östlund. What older people expect of robots: A mixed methods approach. In *Social Robotics*, pages 19–29. Springer, 2013.

[86] B. Reeves and C. Nass. The media equation: How people treat computers, television, and new media like real people and places. In *New York: Cambridge University Press.*, 1996.

[87] Humza Qadir Raja and Oliver Scholz. A case study on self-sufficiency of individual robotic modules in an arena with limited energy resources. In *ADAPTIVE 2011, The Third International Conference on Adaptive and Self-Adaptive Systems and Applications*, pages 29–35, 2011.

[88] Maja J Mataric. Minimizing complexity in controlling a mobile robot population. In *Proceedings in IEEE International Conference on Robotics and Automation*, pages 830–835. IEEE, 1992.

[89] Ronald C Arkin, Tucker Balch, and Elizabeth Nitz. Communication of behavorial state in multi-agent retrieval tasks. In *Robotics and Automation, 1993. Proceedings., 1993 IEEE International Conference on*, pages 588–594. IEEE, 1993.

[90] Ken Sugawara and Toshinori Watanabe. A study on foraging behavior of simple multi-robot system. In *IECON 02 [Industrial Electronics Society, IEEE 2002 28th Annual Conference of the]*, volume 4, pages 3085–3090. IEEE, 2002.

[91] David McFarland. Towards robot cooperation. *From animals to animats*, 3:440–444, 1994.

[92] David McFarland. Animal robotics-from self-sufficiency to autonomy. In *From Perception to Action Conference, 1994., Proceedings*, pages 47–54. IEEE, 1994.

[93] David McFarland and Emmet Spier. Basic cycles, utility and opportunism in self-sufficient robots. *Robotics and Autonomous Systems*, 20(2):179–190, 1997.

[94] Masao Kubo and Chris Melhuish. Robot trophallaxis: Managing energy autonomy in multiple robots. *Proceedings of Towards Autonomous Robotic Systems*, 2004.

[95] François Michaud and Jonathan Audet. Using motives and artificial emotions for long-term activity of an autonomous robot. In *Proceedings of the fifth international conference on Autonomous agents*, pages 188–189. ACM, 2001.

[96] François Michaud and Etienne Robichaud. Sharing charging stations for long-term activity of autonomous robots. In *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, volume 3, pages 2746–2751. IEEE, 2002.

[97] S. Kernbach. *Improving the Scalability of Collective Systems*. Springer-Verlag Berlin, 2010.

[98] Trung Dung Ngo, H. Raposo, and H. Schioler. Being sociable: Multirobots with self-sustained energy. In *MED '07. Mediterranean Conference on Control Automation, 2007.*, pages 1–6, June 2007.

[99] Ioannis Ieropoulos, John Greenman, and Chris Melhuish. Imitating metabolism: Energy autonomy in biologically inspired robots. In *Proceedings of the AISB*, volume 3, pages 191–4, 2003.

[100] MP Golombek, RA Cook, T Economou, WM Folkner, AFC Haldemann, PH Kallemeyn, Jens Martin Knudsen, RM Manning, HJ Moore, TJ Parker, et al. Overview of the mars pathfinder mission and assessment of landing site predictions. *Science*, 278(5344):1743–1748, 1997.

[101] Ian Kelly, Owen Holland, and Chris Melhuish. Slugbot: A robotic predator in the natural world. In *Proceedings of the Fifth International Symposium on Artificial Life and Robotics for Human Welfare and Artificial Liferobotics*, pages 470–475. Citeseer, 2000.

[102] Ioannis Ieropoulos, Chris Melhuish, John Greenman, and Ian Horsfield. Ecobot-ii: An artificial agent with a natural metabolism. *Journal of Advanced Robotic Systems*, 2(4):295–300, 2005.

[103] Kerstin Severinson-Eklundh, Anders Green, and Helge Hüttenrauch. Social and collaborative aspects of interaction with a service robot. *Robotics and Autonomous Systems*, 42(3–4):223 – 234, 2003. Socially Interactive Robots.

[104] H. Huttenrauch and Eklundh K.S. Fetch-and-carry with cero: observations from a long-term user study with a service robot. In *RO-MAN*, pages 158–163, 2002.

[105] Tomas Krajnik, Jaime P Fentanes, Oscar M Mozos, Tom Duckett, Johan Ekekrantz, and Marc Hanheide. Long-term topological localisation for service robots in dynamic environments using spectral maps. In *Intelligent Robots*

and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on, pages 4537–4542. IEEE, 2014.

[106] Joydeep Biswas and Manuela M Veloso. Localization and navigation of the cobots over long-term deployments. *The International Journal of Robotics Research*, 32(14):1679–1694, 2013.

[107] N. Tomatis, G. Terrien, R. Piguet, D. Burnier, S. Bouabdallah, K.O. Arras, and R. Siegwart. Designing a secure and robust mobile interacting robot for the long term. In *Robotics and Automation, 2003. Proceedings. ICRA '03. IEEE International Conference on*, volume 3, pages 4246–4251, Sept 2003.

[108] K. Stubbs, D. Bernstein, K. Crowley, and I. Nourbakhsh. Long-term human-robot interaction: The personal exploration rover and museum docents. In *In Proceeding of the 2005 conference on Artificial Intelligence in Education: Supporting Learning through Intelligent and Socially Informed Technology.*, IOS Press, pages 621–628, 2005.

[109] T. Kanda, M. Shiomi, Z. Miyashita, H. Ishiguro, and N. Hagita. A communication robot in a shopping mall. *Robotics, IEEE Transactions*, 26(5):897–913, Oct 2010.

[110] Takayuki Kanda, Takayuki K, Takayuki Hirano, Daniel Eaton, and Hiroshi Ishiguro. A practical experiment with interactive humanoid robots in human society, 2003.

[111] Fumihide Tanaka, Aaron Cicourel, and Javier R Movellan. Socialization between toddlers and robots at an early childhood education center. *Proceedings of the National Academy of Sciences*, 104(46):17954–17958, 2007.

[112] Takayuki Kanda, Rumi Sato, Naoki Saiwaki, and Hiroshi Ishiguro. A two-month field trial in an elementary school for long-term human–robot interaction. *Robotics, IEEE Transactions on*, 23(5):962–971, 2007.

[113] K. Wada and T. Shibata. Robot therapy in a care house - results of case studies. In *The 15th IEEE International Symposium on Robot and Human Interactive Communication*, pages 581–586, Sept 2006.

[114] K. Wada and T. Shibata. Living with seal robots-its sociopsychological and physiological influences on the elderly at a care house. volume 23, pages 972–980, Oct 2007.

[115] Ylva Fernaeus, Maria Håkansson, Mattias Jacobsson, and Sara Ljungblad. How do you play with a robotic toy animal?: a long-term study of pleo. In *Proceedings*

of the 9th international Conference on interaction Design and Children, pages 39–48. ACM, 2010.

[116] JaYoung Sung, Rebecca E Grinter, and Henrik I Christensen. Domestic robot ecology. *International Journal of Social Robotics*, 2(4):417–429, 2010.

[117] JaYoung Sung, Henrik I. Christensen, and Rebecca E. Grinter. Robots in the wild: Understanding long-term use. In *Proceedings of the 4th ACM/IEEE International Conference on Human Robot Interaction*, HRI '09, pages 45–52, 2009.

[118] Julia Fink, Valérie Bauwens, Frédéric Kaplan, and Pierre Dillenbourg. Living with a vacuum cleaning robot. *International Journal of Social Robotics*, 5(3):389–408, 2013.

[119] Guy Hoffman, Herzliya, and Wendy Ju. Designing robots with movement in mind. *Journal of Human-Robot Interaction*, 3(32):89–122, 2014.

[120] E.T Hall. *The Hidden Dimension.* Doubleday, New York, 1966.

[121] JUDEE K. BURGOON and JOSEPH B. WALTHER. Nonverbal expectancies and the evaluative consequences of violations. *Human Communication Research*, 17(2):232–265, 1990.

[122] M.L. Walters, M.A Oskoei, D.S. Syrdal, and K. Dautenhahn. A long-term human-robot proxemic study. In *RO-MAN, 2011 IEEE*, pages 137–142, July 2011.

[123] Julia Fink. Dynamics of human-robot interaction in domestic environments. 2014.

[124] Stephanie Rosenthal, Joydeep Biswas, and Manuela Veloso. An effective personal mobile robot agent through symbiotic human-robot interaction. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: volume 1-Volume 1*, pages 915–922. International Foundation for Autonomous Agents and Multiagent Systems, 2010.

[125] Rachel Kirby, Frank Broz, Jodi Forlizzi, Marek Piotr Michalowski, Anne Mundell, Stephanie Rosenthal, Brennan Peter Sellner, Reid Simmons, Kevin Snipes, Alan Schultz, and Jue Wang. Designing robots for long-term social interaction. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2005)*, pages 2199 – 2204. IEEE, August 2005.

[126] Sara Ljungblad and Lars Erik Holmquist. Designing robot applications for everyday environments. In *Proceedings of the 2005 joint conference on Smart objects and ambient intelligence: innovative context-aware services: usages and technologies*, pages 65–68. ACM, 2005.

[127] Mattias Jacobsson, Sara Ljungblad, Johan Bodin, Jeffrey Knurek, and Lars Erik Holmquist. Glowbots: robots that evolve relationships. In *ACM SIGGRAPH 2007 emerging technologies*, page 7. ACM, 2007.

[128] Hyunsoo Song, Min Joong Kim, Sang-Hoon Jeong, Hyen-Jeong Suk, and Dong-Soo Kwon. Design of idle motions for service robot via video ethnography. In *Robot and Human Interactive Communication, 2009. RO-MAN 2009.*, Sept 2009.

[129] John D Gould and Clayton Lewis. Designing for usability: key principles and what designers think. *Communications of the ACM*, 28(3):300–311, 1985.

[130] Sara Ljungblad, Katarina Walter, Mattias Jacobsson, and Lars Erik Holmquist. Designing personal embodied agents with personas. In *Robot and Human Interactive Communication, 2006. ROMAN 2006. The 15th IEEE International Symposium on*, pages 575–580. IEEE, 2006.

[131] J Osada, S Ohnaka, and M Sato. The scenario and design process of childcare robot. *PaPeRo, Dynamic Indoor Environments*, pages 80–86, 2006.

[132] Bernt Meerbeek, Martin Saerbeck, and Christoph Bartneck. Iterative design process for robots with personality. In *AISB2009 Symposium on New Frontiers in Human-Robot Interaction. SSAISB*. Citeseer, 2009.

[133] Rianne Appel-Meulenbroek, Peter Groenen, and Ingrid Janssen. An end-user's perspective on activity-based office concepts. *Journal of Corporate Real Estate*, 13(2):122–135, 2011.

[134] Timothy A Judge and Daniel M Cable. The effect of physical height on workplace success and income: preliminary test of a theoretical model. *Journal of Applied Psychology*, 89(3):428, 2004.

[135] Michael L Walters. *The design space for robot appearance and behaviour for social robot companions*. PhD thesis, School of Computer Science, Faculty of Engineering and Information Sciences, University of Hertfordshire, 1908.

[136] Min Kyung Lee, Jodi Forlizzi, Paul E Rybski, Frederick Crabbe, Wayne Chung, Josh Finkle, Eric Glaser, and Sara Kiesler. The snackbot: documenting the

design of a robot for long-term human-robot interaction. In *Human-Robot Interaction (HRI), 2009 4th ACM/IEEE International Conference on*, pages 7–14. IEEE, 2009.

[137] Irene Rae, Leila Takayama, and Bilge Mutlu. The influence of height in robot-mediated communication. In *Proceedings of the 8th ACM/IEEE international conference on Human-robot interaction*, pages 1–8. IEEE Press, 2013.

[138]

[139] Jan Kedzierski, Robert Muszynski, Carsten Zoll, Adam Oleksy, and Mirela Frontkiewicz. Emys-emotive head of a social robot. *International Journal of Social Robotics*, 5(2):237–249, 2013.

[140] Howie M Choset. *Principles of robot motion: theory, algorithms, and implementation*. MIT press, 2005.

[141] Sebastian Thrun and Arno Bücken. Integrating grid-based and topological maps for mobile robot navigation. In *Proceedings of the National Conference on Artificial Intelligence*, pages 944–951, 1996.

[142] Ding Fu-guang, Jiao Peng, Bian Xin-qian, and Wang Hong-Jian. Auv local path planning based on virtual potential field. In *Mechatronics and Automation, 2005 IEEE International Conference*, volume 4, pages 1711–1716. IEEE, 2005.

[143] Min Cheol Lee and Min Gyu Park. Artificial potential field based path planning for mobile robots using a virtual obstacle concept. In *Advanced Intelligent Mechatronics, 2003. AIM 2003. Proceedings. 2003 IEEE/ASME International Conference on*, volume 2, pages 735–740. IEEE, 2003.

[144] Stephanie Rosenthal and Manuela M Veloso. Mobile robot planning to seek help with spatially-situated tasks. In *AAAI*, volume 4, page 1, 2012.

[145] Reid Simmons and Sven Koenig. Probabilistic navigation in partially observable environments. In *In: Proceedings of the fourteenth international joint conference on artificial intelligence*, pages 1080–1087, 1995.

[146] Chiara Fulgenzi, Christopher Tay, Anne Spalanzani, and Christian Laugier. Probabilistic navigation in dynamic environment using rapidly-exploring random trees and gaussian processes. In *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*, pages 1056–1062. IEEE, 2008.

[147] Hugh Durrant-Whyte and Tim Bailey. Simultaneous localization and mapping: part i. *Robotics & Automation Magazine, IEEE*, 13(2):99–110, 2006.

[148] Yasushi Hada and S Yuta. Robust navigation and battery re-charging system for long term activity of autonomous mobile robot. In *Proceedings of the 9th International Conference on Advanced Robotics*, pages 297–302, 1999.

[149] Gary Bradski. The opencv library. *Doctor Dobbs Journal*, 25(11):120–126, 2000.

[150] Joshua R Smith, Kenneth P Fishkin, Bing Jiang, Alexander Mamishev, Matthai Philipose, Adam D Rea, Sumit Roy, and Kishore Sundara-Rajan. Rfid-based techniques for human-activity detection. *Communications of the ACM*, 48(9):39–44, 2005.

[151] Stephen A Weis, Sanjay E Sarma, Ronald L Rivest, and Daniel W Engels. Security and privacy aspects of low-cost radio frequency identification systems. In *Security in pervasive computing*, pages 201–212. Springer, 2004.

[152] Paul Viola and Michael J Jones. Robust real-time face detection. *International journal of computer vision*, 57(2):137–154, 2004.

[153] M. L. Walters, K. L. Koay, S. N. Woods, D. S. Syrdal, and K. Dautenhahn. Robot to human approaches: Comfortable distances and preferences. In *AAAI Spring Symposium on Multidisciplinary Collaboration for Socially Assistive Robotics*. Stanford University, USA, 2007.

[154] M. L. Walters, K. Dautenhahn, S. N. Woods, K. L. Koay, R. te Boekhorst, and D. Lee. Exploratory studies on social spaces between humans and a mechanical-looking robot. *Journal of Connection Science, Special Issue on Android Science*, 18:429–442, 2006.

[155] Annika Peters, Thorsten P Spexard, Marc Hanheide, Petra Weiss, et al. Hey robot, get out of my way: survey on a spatial and situational movement concept in hri. 2011.

[156] H. Hüttenrauch, K. Severinson Eklundh, A. Green, and E. A. Topp. Investigating spatial relationships in human-robot interaction. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2006)*, pages 5052–5059. Bejing, China, 2006.

[157] http://perso.telecom-paristech.fr/ pelachau/greta/. In *GRETA: Embodied Conversational Agent*.

[158] João Dias and Ana Paiva. Feeling and reasoning: A computational model for emotional characters. In *Progress in artificial intelligence*, pages 127–140. Springer, 2005.

[159] Michael Bratman. Intention, plans, and practical reason. 1987.

[160] Andrew Ortony. *The cognitive structure of emotions.* Cambridge university press, 1990.

[161] Michael Kriegel, Ruth Aylett, Pedro Cuba, Marco Vala, and Ana Paiva. Robots meet ivas: a mind-body interface for migrating artificial intelligent agents. In *Intelligent Virtual Agents*, pages 282–295. Springer, 2011.

[162] K Du Casse, KL Koay, WC Ho, and K Dautenhahn. Reducing the cost of robotics software: Samgar, a generic modular robotic software communication architecture. In *Advanced Robotics, 2009. ICAR 2009. International Conference on*, pages 1–6. IEEE, 2009.

[163] Stefan Freyr Stefansson, Bjorn Jonsson, and Kristinn R Thorisson. A yarp-based architectural framework for robotic vision applications. In *VISAPP (1)*, pages 65–68, 2009.

[164] Joao Dias, Samuel Mascarenhas, and Ana Paiva. Fatima modular: Towards an agent architecture with a generic appraisal framework. In *Emotion Modeling*, pages 44–56. Springer, 2014.

[165] John Travis Butler and Arvin Agah. Psychological effects of behavior patterns of a mobile personal robot. *Autonomous Robots*, 10(2):185–202, 2001.

[166] Sally Jo Cunningham and Matt Jones. Autoethnography: a tool for practice and education. In *Proceedings of the 6th ACM SIGCHI New Zealand chapter's international conference on Computer-human interaction: making CHI natural*, pages 1–8. ACM, 2005.

[167] Malrey Lee, Mahmoud Tarokh, and Matthew Cross. Fuzzy logic decision making for multi-robot security systems. *Artificial Intelligence Review*, 34(2):177–194, 2010.

[168] Cory D Kidd and Cynthia Breazeal. Robots at home: Understanding long-term human-robot interaction. In *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*, pages 3230–3235. IEEE, 2008.

[169] Samuel D Gosling, Peter J Rentfrow, and William B Swann Jr. A very brief measure of the big-five personality domains. *Journal of Research in personality*, 37(6):504–528, 2003.

[170] Tatsuya Nomura, Takayuki Kanda, and Tomohiro Suzuki. Experimental investigation into influence of negative attitudes toward robots on human–robot interaction. *Ai & Society*, 20(2):138–150, 2006.

[171] Matthias U Keysermann, Ruth Aylett, Sibylle Enz, Henriette Cramer, Carsten Zoll, and Patricia A Vargas. Investigating trust issues arising from human-robot information sharing. *Proceedings of Autonomous Robots and Multirobot Systems*, 2012.

[172] Tetsuya Nasukawa and Jeonghee Yi. Sentiment analysis: Capturing favorability using natural language processing. In *Proceedings of the 2nd international conference on Knowledge capture*, pages 70–77. ACM, 2003.

[173] Nathan Aston, Jacob Liddle, and Wei Hu. Twitter sentiment in data streams with perceptron. *Journal of Computer and Communications*, 2014, 2014.

[174] Ishan Sudeera Abeywardena. Public opinion on oer and mocc: a sentiment analysis of twitter data. 2014.

[175] Linus Lawrence. Reliability of sentiment mining tools: A comparison of semantria and social mention. 2014.

[176] Jenay M Beer, Akanksha Prakash, Tracy L Mitzner, and Wendy A Rogers. Understanding robot acceptance. 2011.

[177] Cynthia L Breazeal. *Designing sociable robots*. MIT press, 2004.

[178] Mei Yii Lim, Ruth Aylett, Wan Ching Ho, Sibylle Enz, and Patricia Vargas. A socially-aware memory for companion agents. In *Intelligent Virtual Agents*, pages 20–26. Springer, 2009.

[179] Amol A Deshmukh, Mei Yii Lim, Michael Kriegel, Ruth Aylett, Kyron Du Casse, Koay Kheng L, and Kerstin Dautenhahn. Managing social constraints on recharge behaviour for robot companions using memory. In *Proceedings of the 6th international conference on Human-robot interaction*, pages 129–130. ACM, 2011.

[180] Katrin S Lohan, Amol Deshmukh, Mei Yii Lim, and Ruth Aylett. Spotting social interaction by using the robot energy consumption. In *2014 AAAI Fall Symposium Series*, 2014.

[181] Amol Deshmukh and Ruth Aylett. Socially constrained management of power resources for social mobile robots. In *Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction*, pages 119–120. ACM, 2012.

[182] Yongguo Mei, Yung-Hsiang Lu, Y Charlie Hu, and CS George Lee. A case study of mobile robot's energy consumption and conservation techniques. In *Advanced*

Robotics, 2005. ICAR'05. Proceedings., 12th International Conference on, pages 492–497. IEEE, 2005.

[183] Chi-Hong Hwang and Allen C-H Wu. A predictive system shutdown method for energy saving of event-driven computation. *ACM Transactions on Design Automation of Electronic Systems (TODAES)*, 5(2):226–241, 2000.

[184] Tohru Ishihara and Hiroto Yasuura. Voltage scheduling problem for dynamically variable voltage processors. In *Low Power Electronics and Design, 1998. Proceedings. 1998 International Symposium on*, pages 197–202. IEEE, 1998.

[185] R.S. Smith, M.S. Hanlon, and R.L. Bailey. Power management for a laptop computer with slow and sleep modes, nov 1992. US Patent 5,167,024.

[186] Yan-You Chen, Jhing-Fa Wang, Po-Chuan Lin, Po-Yi Shih, Hsin-Chun Tsai, and Da-Yu Kwan. Human-robot interaction based on cloud computing infrastructure for senior companion. In *TENCON 2011-2011 IEEE Region 10 Conference*, pages 1431–1434. IEEE, 2011.

[187] J Dean Brock, Rebecca F Bruce, and Marietta E Cameron. Changing the world with a raspberry pi. *Journal of Computing Sciences in Colleges*, 29(2):151–153, 2013.

[188] John F Kelley. An iterative design methodology for user-friendly natural language office information applications. *ACM Transactions on Information Systems (TOIS)*, 2(1):26–41, 1984.

[189] Astrid Weiss, Regina Bernhaupt, Daniel Schwaiger, Martin Altmaninger, Roland Buchner, and Manfred Tscheligi. User experience evaluation with a wizard of oz approach: Technical and methodological considerations. In *Humanoid Robots, 2009. Humanoids 2009. 9th IEEE-RAS International Conference on*, pages 303–308. IEEE, 2009.

[190] Laurel D Riek. Wizard of oz studies in hri: a systematic review and new reporting guidelines. *Journal of Human-Robot Interaction*, 1(1), 2012.

[191] Wilma A Bainbridge, Justin Hart, Elizabeth S Kim, and Brian Scassellati. The effect of presence on human-robot interaction. In *Robot and Human Interactive Communication, 2008. RO-MAN 2008. The 17th IEEE International Symposium on*, pages 701–706. IEEE, 2008.

[192] Ulrike Bruckenberger, Astrid Weiss, Nicole Mirnig, Ewald Strasser, Susanne Stadler, and Manfred Tscheligi. The good, the bad, the weird: Audience evaluation of a "real" robot in relation to science fiction and mass media. In *Social Robotics*, pages 301–310. Springer, 2013.

[193] Sara Ljungblad, Jirina Kotrbova, Mattias Jacobsson, Henriette Cramer, and Karol Niechwiadowicz. Hospital robot at work: something alien or an intelligent colleague? In *Proceedings of the ACM 2012 conference on Computer Supported Cooperative Work*, pages 177–186. ACM, 2012.

[194] Mattias Jacobsson and Stina Nylander. Always-on+ adoption–a method for longitudinal studies. 2012.

[195] Matthew Lombard and Theresa Ditton. At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication*, 3(2):0–0, 1997.

[196] Carrie Heeter. Being there: The subjective experience of presence. *Presence: Teleoperators and virtual environments*, 1(2):262–271, 1992.

[197] Kwan-Min Lee and Clifford Nass. Social-psychological origins of feelings of presence: Creating social presence with machine-generated voices. *Media Psychology*, 7(1):31–45, 2005.

[198] Paul Schermerhorn, Matthias Scheutz, and Charles R Crowell. Robot social presence and gender: Do females view robots differently than males? In *Proceedings of the 3rd ACM/IEEE international conference on Human robot interaction*, pages 263–270. ACM, 2008.

[199] Iolanda Leite, Ginevra Castellano, André Pereira, Carlos Martinho, and Ana Paiva. Empathic robots for long-term interaction. *International Journal of Social Robotics*, 6(3):329–341, 2014.

[200] Michael L Walters, Manja Lohse, Marc Hanheide, Britta Wrede, Dag Sverre Syrdal, Kheng Lee Koay, Anders Green, Helge Hüttenrauch, Kerstin Dautenhahn, Gerhard Sagerer, et al. Evaluating the robot personality and verbal behavior of domestic robots using video-based studies. *Advanced Robotics*, 25(18):2233–2254, 2011.

[201] Katrin Solveig Lohan, Katharina Rohlfing, Karola Pitsch, Joe Saunders, Hagen Lehmann, Chrydtopher Nehaniv, Kerstin Fischer, and Britta Wrede. Tutor spotter: Proposing a feature set and evaluating it in a robotic system. *International Journal of Social Robotics*, 4:131–146, 2012.

[202] P. Ten Have. *Doing conversation analysis*. Sage Publications Ltd, 2007.

[203] Alvin X Li, Maria Florendo, Luke E Miller, Hiroshi Ishiguro, and Ayse P Saygin. Robot form and motion influences social attention. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction*, pages 43–50. ACM, 2015.

[204] Peter Wittenburg, Hennie Brugman, Albert Russel, Alex Klassmann, and Han Sloetjes. Elan: a professional framework for multimodality research. In *Proceedings of LREC*, 2006.

[205] MATLAB and Statistics Toolbox Release 2012b.

[206] Britta Wrede, Katharina J Rohlfing, Marc Hanheide, and Gerhard Sagerer. Towards learning by interacting. In *Creating Brain-Like Intelligence*, pages 139–150. Springer, 2009.

[207] Astrid Weiss, Regina Bernhaupt, Manfred Tscheligi, Dirk Wollherr, K Kuhnlenz, and Martin Buss. A methodological variation for acceptance evaluation of human-robot interaction in public places. In *Robot and Human Interactive Communication, 2008. RO-MAN 2008. The 17th IEEE International Symposium on*, pages 713–718. IEEE, 2008.

[208] Adam Kendon. *Conducting interaction: Patterns of behavior in focused encounters*, volume 7. CUP Archive, 1990.

[209] Jonathan Mumm and Bilge Mutlu. Human-robot proxemics: physical and psychological distancing in human-robot interaction. In *Proceedings of the 6th international conference on Human-robot interaction*, pages 331–338. ACM, 2011.

[210] Leila Takayama and Caroline Pantofaru. Influences on proxemic behaviors in human-robot interaction. In *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*, pages 5495–5502. IEEE, 2009.

[211] Stuart Watt. A brief naive psychology manifesto. *Informatica*, 19(4):495–500, 1995.

[212] Philipp Althaus, Hiroshi Ishiguro, Takayuki Kanda, Takahiro Miyashita, and Henrik I Christensen. Navigation for human-robot interaction tasks. In *Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on*, volume 2, pages 1894–1900. IEEE, 2004.

[213] Emrah Akin Sisbot, Rachid Alami, Thierry Siméon, Kerstin Dautenhahn, M Walters, and S Woods. Navigation in the presence of humans. In *Humanoid Robots, 2005 5th IEEE-RAS International Conference on*, pages 181–188. IEEE, 2005.

[214] Maria Aarestrup, Lars Christian Jensen, and Kerstin Fischer. The sound makes the greeting: Interpersonal functions of intonation in human-robot interaction. In *2015 AAAI Spring Symposium Series*, 2015.

[215] Brandon Heenan, Saul Greenberg, Setareh Aghel-Manesh, and Ehud Sharlin. Designing social greetings in human robot interaction. In *Proceedings of the 2014 conference on Designing interactive systems*, pages 855–864. ACM, 2014.

[216] Astrid Weiss, Judith Igelsböck, Manfred Tscheligi, Andrea Bauer, Kolja Kühnlenz, Dirk Wollherr, and Martin Buss. Robots asking for directions: the willingness of passers-by to support robots. In *Proceedings of the 5th ACM/IEEE international conference on Human-robot interaction*, pages 23–30. IEEE Press, 2010.

[217] Kerstin Dautenhahn, M Walters, Sarah Woods, Kheng Lee Koay, Chrystopher L Nehaniv, A Sisbot, Rachid Alami, and Thierry Siméon. How may i serve you?: a robot companion approaching a seated person in a helping context. In *Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*, pages 172–179. ACM, 2006.

[218] Helge Hüttenrauch and Kerstin Severinson Eklundh. To help or not to help a service robot. In *Proceedings of the 12th IEEE International Workshop on Robot and Human Interactive Communication ROMAN'2003*, 2003.

[219] Jennifer Goetz, Sara Kiesler, and Aaron Powers. Matching robot appearance and behavior to tasks to improve human-robot cooperation. In *Robot and Human Interactive Communication, 2003. Proceedings. ROMAN 2003. The 12th IEEE International Workshop on*, pages 55–60. IEEE, 2003.

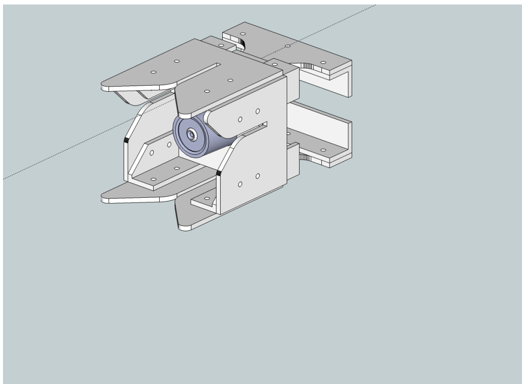
[220] John Frederick Dashiell. Experimental studies of the influence of social situations on the behavior of individual human adults. 1935.

Appendices

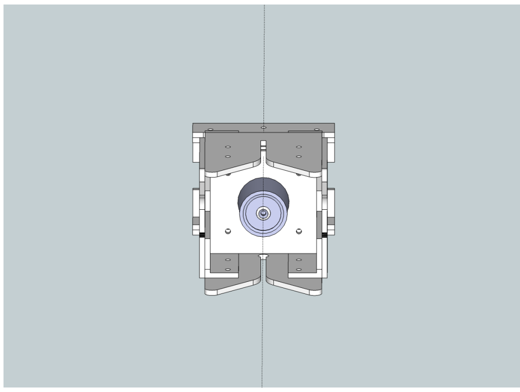
Appendix A

Appendix

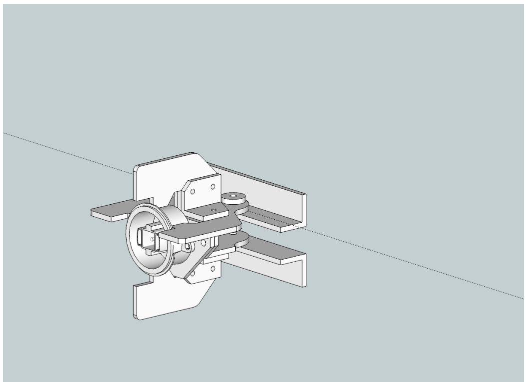
A. 1 Recharge Connectors Designs



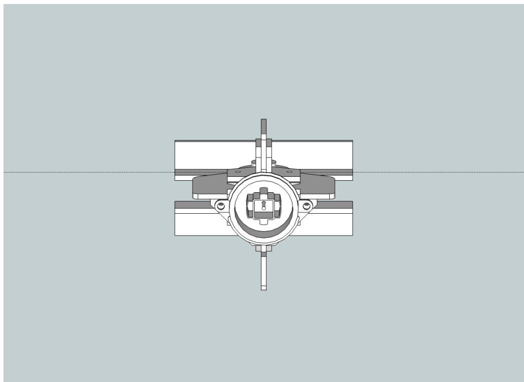
(a) Docking connector side angle



(b) Docking connector front angle



(c) Charging connector side angle



(d) Charging connector front angle

Figure A.1: Recharging connectors designs

A. 2 Modules used on Robot

Figure A.2 shows the modules used on the robot. Blue circles describe the modules and ports and the lines between them show the communication link between them. Table A.1 describes the modules used on the robot.

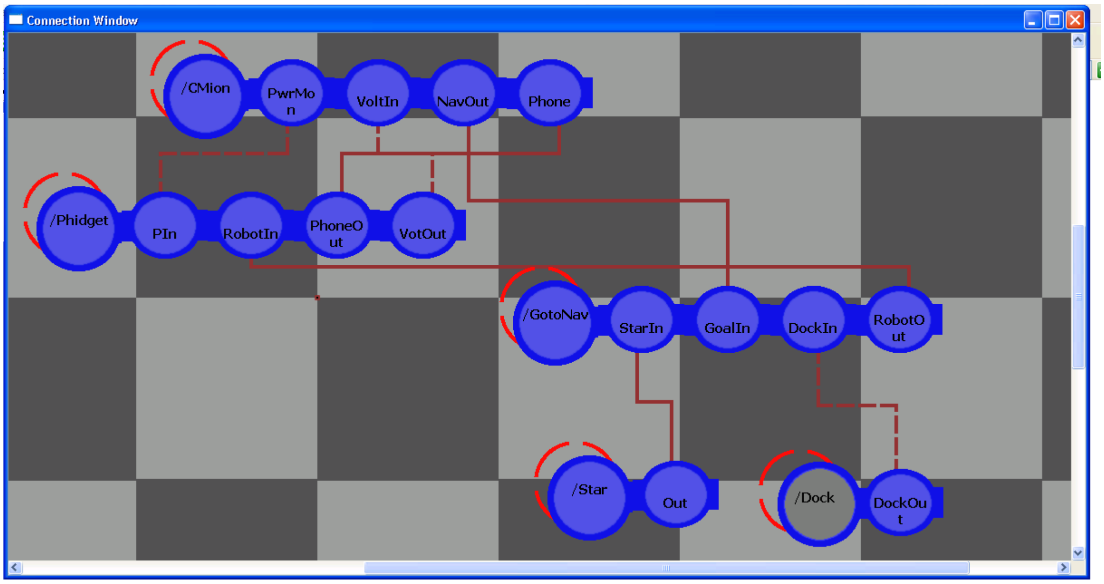


Figure A.2: Samgar [162], an interface used to connect YARP modules [163].

Module	**Ports(Data)**	**Description**
CMion: Perception inputs/outputs	PwrMon(String)	Fuzzy battery status
	VoltIn(Integer)	Battery Voltage
	NavOut(Integer)	Goal position
	Phone(Boolean)	Phone ring status
Phidget: Power monitoring, sensors used on the robot	PIn(String)	Fuzzy battery level
	RobotIn(Integer)	Voltage sensor reading
	PhoneOut(Boolean)	Light sensor reading
	VotOut(Integer)	Voltage from battery
GotoNav: Module resposnsible for navigation	StartIn(Integer, X, Y)	Input from stargazer
	GoalIn(Integer)	Navigation goal position
	DockIn(Boolean)	Docking status
	RobotOut(Boolean)	Navigation status
Star: Stargazer localisation sensor	StarOut(Integer, X, Y)	Position of landmark
Dock: Docking module	DockOut(Boolean)	If docking was successful

Table A.1: Module Description

A. 3 Social Study: Participants Instruction Sheet

Please read this document before entering the room. We are researchers working in the lab you are about to enter. There is a robot, the Team Buddy Alex, an office assistant robot that helps us in the lab. TB cannot hear you but you can talk with Alex using a tablet placed on the body, although using the tablet is optional.

The robot can perform tasks like greeting, passing messages left by other team mates and deliver calls (Please note when you hear phone ring, this is not a real phone call and you can answer using the tablet by pressing Yes/No button)

Bob and Paul are professors at this university who work together in the Lab you are entering. Bob is now on holiday and needs to mark some exams. He has forgotten one in the lab and has asked you to do that for him.

Task:

1) Mark that exam paper by comparing it with the answer sheet provided. Score every question and write the final score on the paper (correct answers give 1 point, incorrect answers -0.5 point and unanswered questions 0 points).

2) Please do not mark or use your pen on the exam paper, there is a separate solution sheet for you mark your points, add the total in the end row. If you see more questions in solution sheet just mark the exam questions you are provided with. Marking the exam paper is not mandatory, but a background task for you

3) You can leave the room after completing the exam marking, but please do not leave the room before the team buddy (robot) has performed two tasks, message delivery and call delivery.

4) Please do not remove the tablet from the robot, keep it back in place once you have used it.

A. 4 Social Study Consent

Team Buddy
Consent Form

Introduction

Thank you for taking part in this Study. Feedback from people not involved in the design of our robot companion is very important to our work. Before we begin our experiment, however, we will need to find out some things about you.

The research will involve some questionnaires. All data collected on individual participants will be treated with full confidentiality. At no time throughout the whole course of the research project will your name or any other personal details that you provide be identifiable, (i.e. your name will not appear in any internal or external publications). All evaluation work will be based on the participant numbers allocated to each subject. This ID code will form the basis of our evaluations, not your real name.

Collected data also includes audio and video recordings of your interaction with the Team Buddy, which helps us improve the Team Buddy's functionality. The recordings will only be used for internal analysis unless you give your explicit consent for us to use them in presentations to an academic audience or for project publicity. But if you do not want this you can still take part in this study.

Participation in this study is entirely voluntary. If at any point you do not wish to continue with the study, you may withdraw, this will not reflect badly on you. The questionnaires provided do not have any right or wrong answers, nor should they be viewed as tests. However, you can decide not to answer certain questions in the questionnaires provided if you do not wish to.

Name:

I consent to take part in this study:

____

I agree to the use of video and audio recordings of my participation in these studies to
be used for presentations to an academic audience or project publicity:

[ ] yes [ ] no

A. 5 Social Study Questionnaire

What is your field of study or work/occupation

Do you use a computer as part of your daily work and studies

- Yes
- No

Do you have experience of using robots, for instance, vacuum-cleaning or lawn-mowing robots? Please specify in other if yes

- Yes
- No
- Other:

Sex *Required

- Male
- Female

Age *Required

- 18-24
- 25-34
- 35-44
- 45-55
- >55

Ethnicity

Part A (Please don't fill in this section if you have not interacted with the robot)

Your experience with the Teambuddy (TB) in the office * Required

Please answer them based on your interaction experience.

1: Disagree strongly, 2: Disagree moderately, 3: Disagree a little, 4: Neither agree nor disagree, 5: Agree a little, 6: Agree moderately, 7: Agree strongly

Question	1	2	3	4	5	6	7
A: I liked it when TB greeted me	○	○	○	○	○	○	○
A: I liked it when TB delivered the message to me	○	○	○	○	○	○	○
A: I liked it when TB delivered the call to me	○	○	○	○	○	○	○
A: I felt in company of TB	○	○	○	○	○	○	○
A: TB was polite	○	○	○	○	○	○	○
A: I noticed the TB clearly	○	○	○	○	○	○	○
A: TB noticed me clearly	○	○	○	○	○	○	○
A: TB was useful	○	○	○	○	○	○	○
A: TB presence was obvious to me	○	○	○	○	○	○	○
A: My presence was obvious to TB	○	○	○	○	○	○	○

A: What was the best aspect of the Teambuddy?

A: If you have any comments, add them here:

A: What was the worst aspect of the Teambuddy?

Part B (Please don't fill in this section if you have not interacted with the robot the second time)
Your experience with the Teambuddy (TB) in the office *Required

Please answer them based on your interaction experience.

1: Disagree strongly, 2: Disagree moderately, 3: Disagree a little, 4: Neither agree nor disagree, 5: Agree a little, 6: Agree moderately, 7: Agree strongly

Question	1	2	3	4	5	6	7
B: I liked it when TB greeted me	○	○	○	○	○	○	○
B: I liked it when TB delivered the message to me	○	○	○	○	○	○	○
B: I liked it when TB delivered the call to me	○	○	○	○	○	○	○
B: I felt in company of the TB	○	○	○	○	○	○	○
B: TB was polite	○	○	○	○	○	○	○
B: TB was useful	○	○	○	○	○	○	○
B: TB noticed me clearly	○	○	○	○	○	○	○
B: I noticed TB clearly	○	○	○	○	○	○	○
B: My presence was obvious to TB	○	○	○	○	○	○	○
B: TB presence was obvious to me	○	○	○	○	○	○	○
B: I did not like the fact that TB was not facing me	○	○	○	○	○	○	○

Please answer them based on importance you think

1: Very Important, 2: Important, 3: Moderately Important, 4: Of Little Importance, 5: Unimportant

Question	1	2	3	4	5
Robots should take care of recharging themselves	◯	◯	◯	◯	◯
Robots should be able to communicate about their limitations/failure	◯	◯	◯	◯	◯
Robots should move while performing tasks	◯	◯	◯	◯	◯
Robots should choose their recharge time wisely	◯	◯	◯	◯	◯
Robots should be able to perform communicative (verbal) tasks even when they are recharging	◯	◯	◯	◯	◯

B: What was the best aspect of the Teambuddy?

B: What was the worst aspect of the Teambuddy?

B: If you have any comments, add them here:

Which team buddy would you prefer Part A or Part B? *Required

◯ Part A ◯ Part B ◯ Both

Why did you prefer Part A/B or Both Team buddy? can you provide a reason? *Required

Additional comments if you have any additional comments please write them here

A. 6 Social Study Questionnaire Comments

P) Preferred Part A or B (P):

Part A (A): 32, Part B (B): 10, Both (N): 8,

Reason: Social 17, Mobility: 28, n/a: 5

No.	**Reason**	**P**	**Category**	**Remark**
P1	better service getting phone delivered	A	Social	use
P2	mobility	A	Mobility	
P3	especially the part where it approached me and introduced himself, was nice; in the second part the robot was standing still at a distance	A	Mobility	
P4	because he moved	A	Mobility	
P5	It feels better when it comes towards you a bit.	A	Mobility	
P6	In part A the robot felt more companion like, that is why I liked it more. However, the second part made me realise he's lifelike since he's got his own needs.	A	Social	companionship
P7	Part A is just more interesting! Part B didn't really seem very useful	A	Social	use
P8	much helpful it can reach me anywhere inside the room	A	Mobility	
P9	vivid	A	n/a	
P10	I feel the robot can help, and it's better if he can move closer to me, so I don't need to walk	A	Mobility	
P11	The robot moved towards me so I didn't need to travel as far.	A	Mobility	
P12	Because it was mobile. Since I had to walk less to reach the tablet/phone I felt it was less disruptive	A	Mobility	
P13	I did not need to move too far to answer his disruptive calls.	A	Mobility	

P14	Part A made my life easier because it came towards me and delivered all necessary information and helped me perform my tasks. Part B was quite disruptive	A	Mobility	
P15	Part A as it felt more interactive while team buddy faced me, indicating that it knows where i was	A	Social	Presence
P16	Because he was coming to me to give messages	A	Mobility	
P17	more functionality	A	Social	use
P18	I prefer A as it can move and more lively	A	Mobility	
P19	More personal moving towards me instead of facing the wall. Facing me but not moving wouldn't have been very different to A for me.	A	Mobility	
P20	I preferred part A because TB was able to interact with me and moving toward me better than in part B	A	Mobility	
P21	A was both mobile and communicative	A	Mobility	
P22	he moves and more interact	A	Mobility	
P23	It seemed more useful that it could move around	A	Mobility	
P24	she moves to me!	A	Mobility	
P25	Reduce need to leave desk	A	Mobility	
P26	I preferred A as TB moved towards me and spoke to me (facing) and it felt like the room wasn't so empty.	A	Social	Presence
P27	Because by moving TB make my life easier, and should actually move even closer to me to bring the tablet to my desk. TB part B was kind of useless and more disruptive especially if we are considering the end of a tiring busy day.	A	Mobility	
P28	bit more interaction- novelty (however this may wear off)	A	Social	novelty
P29	More interaction in part A	A	Social	interaction
P30	IT WAS MOVING	A	Mobility	

P31	The robot was moving to me and was easier to interact with.	A	Mobility	
P32	Part A interrupts less my work. Part B was more like an obstacle of the work.	A	Social	interruption
P33	I liked knowing where the Team Buddy was and I didn't feel as though it was watching me.	B	Social	Presence
P34	Because it was not facing me or coming towards me. I also got a little bit used to it	B	Social	Presence
P35	The movement was the most disconcerting part. Even though you could get used to it, given enough time.	B	Mobility	
P36	I liked part B as the tem buddy goes silent while it's charging	B	Social	interaction
P37	I didn't like the noise from TB when TB was moving	B	Mobility	noise
P38	I had the earlier experience in which to become accustomed to TB. So I knew what to expect second time around.	B	Social	novelty
P39	I liked how the robot was in standby mode and not moving all around the place unless needed.	B	Mobility	
P40	Part B. Less of a feeling of it looming over you. Didn't have to wait for it to slowly trundle over before performing the task.	B	Mobility	
P41	I didn't like it moving around	B	Mobility	
P42	movement of robot made me uncomfortable and did not like the face, as robot didn't move or face me in part B it was much better	B	Mobility	
P43	n/a	N	n/a	
P44	n/a	N	n/a	
P45	both	N	n/a	
P46	I like to do a new things	N	n/a	
P47	Both because it showed the robot at different circumstances and when interacting with a robot, one would	N	Social	interaction

	have to face both instances, whilst recharging also whilst fully-functional			
P48	It was the same thing -- just interacting in different circumstances (charged/not charged). The behaviour was appropriate in both contexts.	N	Social	interaction
P49	I wouldn't consider the TB's behaviour as so fundamentally different in A to B. He just needed to recharged and if he takes care of that himself that's perfectly fine for me.	N	Social	interaction
P50	part A was efficient but very clinical. Part B was exposing a "disability". I liked them both but I think I would also like it if I could converse more with it.	N	Social	interaction

S) Social TB: N=25, Participant feedback:

Preferred (P) Part A (A) , Part B (B), Both (N):

Category (Cat) -Best: Interaction (I): 3, Utility (U): 4, Verbal (V): 12, Others (O): 1, Social (S): 2, n/a: 3

Category (Cat) -Worst: Interaction (I): 2, Utility (U): 1, Face (F): 5, Others (O): 3, Mobility (M): 10, n/a: 6

N	Part B: What was the best aspect of the TB?	Cat	Part B: What was the worst aspect of the TB?	Cat	P
S1	n/a	n/a	n/a	n/a	A
S2	The apology	V	it didn't face towards me	F	A
S3	Being responsible	S	It cannot move while recharging	M	A
S4	Voice	V	The need to give responses by tablet rather than speaking	I	B
S5	ability to deliver message even when charging	U	not moving towards me when receiving a call	M	B
S6	Easy to understand and interact with (as did not	I	It was facing away from me - less personal.	F	A

	rely on voice recognition)				
S7	It was polite	V	It couldn't move while charging	M	A
S8	Communicative	V	Non mobile	M	A
S9	the service he did	U	not facing me or move	F, M	A
S10	Being able to tell me why it wasn't able to move towards me	V	Not being able to move	M	A
S11	TB informing me that she on recharge	V	n/a	n/a	A
S12	Face	I	Movement	M	A
S13	Again providing me with updates about the office.	V	I would have liked for TB to face me whilst charging and again have the tablet in a more accessible location.	F	A
S14	Voice	V	n/a	n/a	N
S15	He still worked, even though he was recharging	U	He didn't respond to my human interaction like for ex. thanking him	I	N
S16	Announced it would unable to move towards me.	V	Feels more disruptive if you have to go over it. No advantage taking the call yourself.	M	B
S17	TB could talk even with a low battery	V	TB could not move which make the effort to move to TB more annoying especially while you are working. There is a sort of submission of human to robot, if I have to move to the robot. I did not like it because it actually make my life more complicated than easier	M	A
S18	I liked the way it greeted me when I came in and told me it was recharging	V	n/a	n/a	A
S19	n/a	n/a	n/a	n/a	A
S20	interacting with it	I	low battery	O	N

S21	CONVENTIONAL	O	VERY SLOW	O	A
S22	It was still able to interact with me.	U	It was not facing me during charging.	F	A
S23	Contact	S	Unnaturalness	O	B
S24	friendly tone of voice	V	none	n/a	B
S25	n/a	n/a	in Part B it was not really useful	U	A

N) Neutral TB: N=25, Participant feedback:

Preferred (P) Part A (A) , Part B (B), Both (N):

Category (Cat) -Best: Verbal (V): 11, Face (F): 1, Others (O): 2, Social (S): 1, Utility (U): 6, n/a: 4

Category (Cat) -Worst: Face (F): 3, Others (O): 3, Mobility (M): 7, Interaction (I): 7, n/a: 5

N	Part B: What was the best aspect of the TB?	Cat	Part B: What was the worst aspect of the TB?	Cat	P
N1	verbal notifications	V	not moving, no hearing	M	A
N2	recharging herself	O	interface through tablet	I	A
N3	explaining about having to recharge	V	unable to understand what i was saying	I	A
N4	The talking when charging	V	artificial looking	O	A
N5	Still can interact though charging.	U	Didn't face me, was quite far from me.	F	A
N6	He was aware of his condition and made a decision about himself	O	I felt a bit neglected. He could've been more interactive even without moving.	M	A
N7	Keeping informed of the battery status	V	None	n/a	N
N8	I liked its friendly manner and willingness to be helpful	S	n/a	n/a	B
N9	It was not facing me so I did not feel threatened	F	Just a minor one having to go towards it	M	B
N10	Very clear about its limitations	V	Wasn't able to respond to verbal instructions	I	A

N11	n/a	n/a	had to check message while it charging	I	A
N12	n/a	n/a	n/a	n/a	N
N13	charging its battery and replying	V	reply to "hi" and similar was just "ok, i got it"	I	N
N14	n/a	n/a	not facing me	F	A
N15	He's still capable with the easy tasks even when he's charging	U	None as I can see so far	O	A
N16	It choosing to recharge is a good thing.	U	n/a	n/a	B
N17	Automatic recharge	U	Not being able to move while recharging.	M	A
N18	n/a	n/a	n/a	n/a	N
N19	Cordial attitude and telling me why that because it was recharging it would not move.	V	Not moving + having to type on tablet.	M,I	A
N20	Team buddy was able to function whilst recharging.	U	The phone kept ringing even after I had answered the call.	I	N
N21	Nothing special. It only delivers the message	U	Disruptive and not available when required	S	A
N22	Informed me that it was recharging just after he noticed me, performed every task however it could not move	V	It didn't move, so I had to stand up to perform the tasks, I felt this was disruptive and I had to put effort in it	M	A
N23	Easily understandable	V	the loud noise it makes while running	M	B
N24	verbal communication	V	low battery	O	B
N25	The way that it communicated the difference between a message and a phone call	V	That while charging, team buddy faced away from me. would be better to if it was able to recharge at a slight angle to the office space, so not to imply its 'ignoring you'	F	A

A) Additional comments Part A & B

N.	**Part A: If you have any comments, add them here:**	**Part B: If you have any comments, add them here:**
A1	n/a	n/a
A2	n/a	n/a
A3	Giving responses should be more informative so that it can be more user-friendly	No comments
A4	During the experiment i wished to talk to the robot but was inhibited due to needing to use the tablet. I would have spoken had there been speech recognition used.	n/a
A5	n/a	n/a
A6	n/a	n/a
A7	n/a	n/a
A8	Could come even closer. Don't move before starting to talk. Its weird and a bit scary.	n/a
A9	to be more good looking	should be move while charging
A10	The accent made it seem more friendly and natural	n/a
A11	n/a	n/a
A12	The eye's are reassuring	Like the voice too
A13	Really impressive, the robot didn't get in the way and provided a real neat service, which I could see being used in future.	I really enjoyed it - didn't mind the recharge - but I did like initially how TB would move towards me and face me.
A14	n/a	Tablet was still annoying
A15	I think that TB should come even closer to the test candidate, so he/she doesn't have to stop the task of marking the exam and get up to interact with TB.	n/a
A16	n/a	n/a

A17	I am not sure if TB make what a tablet can already do easier or actually more tough. A tablet can alert me as well when I received a message, or a call, and it can be on my desk next to me, I don't need to stand up to pick up the tablet on TB. In addition, the mode silence on tablet is an advantage when you need to be focus. Conversely, TB talk and a silent mode on TB may destroy the robot concept, so I still don't know if I would like to have someone/something that comes to me to notify me from an email or a call...	Maybe TB should be on off mode while recharging instead of half-available which would avoid negative feelings
A18	if one could interact through speech it would have been more natural but regardless she was good company	The call was an interruption but that would have happened anyway regardless of whether the robot told me about it or not
A19	n/a	n/a
A20	i think that it would be useful to have this in my lab!	there more you use it, the more it grows on you
A21	NONE	n/a
A22	Voice recognition would have been good	It could face other way while charging so it feels more human like.
A23	I felt quite disconcerted	n/a
A24	face twitching was a bit creepy	n/a
A25	n/a	n/a
A26	more natural interaction via speech would be good	in this setup/domain, moving seems to be essential
A27	Would be nice to be able to interact with it more naturally	n/a
A28	I don't think the task of sending the marks was completed	n/a
A29	n/a	n/a
A30	It is quite weird when a robot talks to you about some casual work.	n/a

A31	n/a	n/a
A32	Listening would have been great!	-
A33	n/a	n/a
A34	n/a	n/a
A35	n/a	I didn't feel that the mobile platform achieved much- all the tasks could be (and are) done on computer desktops so the actual tasks seemed a bit forced, hard to see any added value
A36	n/a	n/a
A37	n/a	n/a
A38	n/a	n/a
A39	I could not know how to send the desired message	There are redundant choices
A40	It might be better if he can go toward me while I'm sitting at a desk	Although he couldn't move toward me, but it's still alright because he's charging.
A41	n/a	n/a
A42	n/a	n/a
A43	n/a	n/a
A44	n/a	n/a
A45	I am very impressed by this project and it interests me greatly.	To agree to the fact that Teambuddy is useful, the tablet would have to be wireless or closer to the desk, as a phone or computer would be. The act of getting up to interact with the robot, whilst not particularly a bother to me, would not be seen as practical in an actual office.
A46	I could not interact with the robot when I wanted to do so. There should be an option.	It can be controlled by our own will
A47	n/a	Moving while performing a task is quite important as it maximizes the experience. In an office environment where the employee can not stand up and move you expect the robot to do it

A48	I think initially it's uncomfortable when it advances towards you, but you get used to it quickly	n/a
A49	would be better if TB lets me decide whether I want to listen to the message	n/a
A50	n/a	n/a

A. 7 Social Study: Mobile vs Stationary Summary

Factor	p, Sig. (2-tailed)	Z
Greeting	0.763	-.302b
Message	0.007	-2.681b
Call	0.026	-2.223b
Companionship	0.008	-2.638b
Politeness	0.033	-2.138b
Usefulness	0.001	-3.294b
I noticed the TB	0.048	-1.977b
The TB noticed me	0.004	-2.853b
TB Presence was obvious to me	0.001	-3.185b
My Presence Obvious to TB	0.47	-.722b

Table A.2: Mobile vs Stationary: Wilcoxon Ranked Test Summary

A. 8 Social Study: Social vs Neutral Summary

Factor	Mann-Whitney U	Wilcoxon	Z	p
Greeting	269	594	-0.881	0.383
Message	255	580	-1.155	0.25
Call	289	614	-0.464	0.649
Overall	298	623	-0.288	0.776
Companionship	212	537	-1.981	0.048
Politeness	247	572	-1.353	0.193
Usefulness	219.5	544.5	-1.869	0.062
I noticed TB	305.5	630.5	-0.143	0.891
TB noticed me	187	512	-2.485	0.012
TB Presence Obvious to me	305	630	-0.149	0.884
My Presence Obvious to TB	263	588	-0.98	0.333

Table A.3: Social vs Neutral Mann-Whitney U Tests Summary

A. 9 Selected Publications

The work reported in this thesis has been published at different events as follows.

- Katrin S. Lohan, Amol Deshmukh, Mei Yii Lim, Ruth Aylett, “Spotting social interaction by using the robot energy consumption”, AAAI 2014 Fall Symposium on Artificial Intelligence for Human-Robot Interaction, Arlington, VA, USA.

- Katrin Solveig Lohan, Amol Deshmukh, Ruth Aylett, “How Can a Robot Signal Its Incapability to Perform a Certain Task to Humans in an Acceptable Manner?”, In Proceedings of the 23rd IEEE International Symposium on Robot and Human Interactive Communication (IEEE RO-MAN 2014), Edinburgh, Scotland, 2014

- Amol A. Deshmukh, Ruth Aylett, “Exploring socially intelligent recharge behaviour for human-robot interaction”. ACM/IEEE International Conference on Human-Robot Interaction, March 3–6, 2014, Bielefeld, Germany, Late breaking report.

- Amol Deshmukh, Ruth Aylett, “Socially Constrained Management Of Power Resources For Social Mobile Robots”, ACM/IEEE International Conference on Human-Robot Interaction March, 2012, Boston, Massachusetts, USA, Late breaking report.

- Amol Deshmukh, R. Aylett, “Socially Constrained Management Of Power Resources For Social Mobile Robots”, (Workshop) International Conference on Social Robotics, 2011, November, Amsterdam.

- Amol Deshmukh, M. Yii Lim, M. Kriegel, R. Aylett, K.D. Casse, K.L. Koay, K. Dautenhahn, “Managing Social Constraints on Recharge for Robot Companions Using Memory”, ACM/IEEE International Conference on Human-Robot Interaction 2011, 6-9 March, Lausanne, Switzerland

- Amol Deshmukh, Castellano G, Lim MY, Aylett R, McOwan PW, “Ubiquitous Social Perception Abilities for Interaction Initiation in Human-Robot Interaction”. ACM Multimedia 2010 Workshop - Affective Interaction in Natural Environments (AFFINE), Florence, Italy, October 2010

- Amol A. Deshmukh, Patricia A. Vargas, Ruth Aylett and Keith Brown, “Towards Socially Constrained Power Management for Long-Term Operation of Mobile Robots”, 11th Conference Towards Autonomous Robotic Systems, Plymouth, UK, September 2010

A. 10 Other Resources

- Docking Trial Video: This video shows the robot autonomously docking into the charging station.
  Link:`http://www.macs.hw.ac.uk/~amol/download/phd/DockingTrial.mp4`

- Long-Term Study Video 1: This video shows an example of interaction during long-term study from room camera. The TB delivers a message to one participant and then the other.
  Link: `http://www.macs.hw.ac.uk/~amol/download/phd/TBOfficeCamera.mp4`

- Long-Term Study Video 2: This video shows an example of interaction from robot's camera perspective, a visitor leaving a message for a user and the TB delivering it.
  Link: `http://www.macs.hw.ac.uk/~amol/download/phd/TBRobotCam.mp4`

- Long-Term Study: The full transcription of the interviews is available at: `http://www.macs.hw.ac.uk/~amol/download/phd/InterviewTranscription.pdf`.

- Social Study Video: This video demonstrates the social study, part A (mobile) and part B (Stationary) conditions.
  Link: `http://www.macs.hw.ac.uk/~amol/download/phd/Social_Study.mp4`

- Social Study Distance Measurement Video:
  `http://www.macs.hw.ac.uk/~amol/download/phd/DistanceMeasurement.mp4`

- Source Code: The source code for all modules used on the robot, the main project file is Project.sln (requires visual studio).
  Link: `http://www.macs.hw.ac.uk/~amol/download/phd/Code.zip`